



**US Army Corps
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Waterways Experiment
Station

Technical Report EL-97-8
April 1997

Environmental Impact Research Program

Bioengineering for Streambank Erosion Control

Report 1 Guidelines

by Hollis H. Allen, James R. Leech

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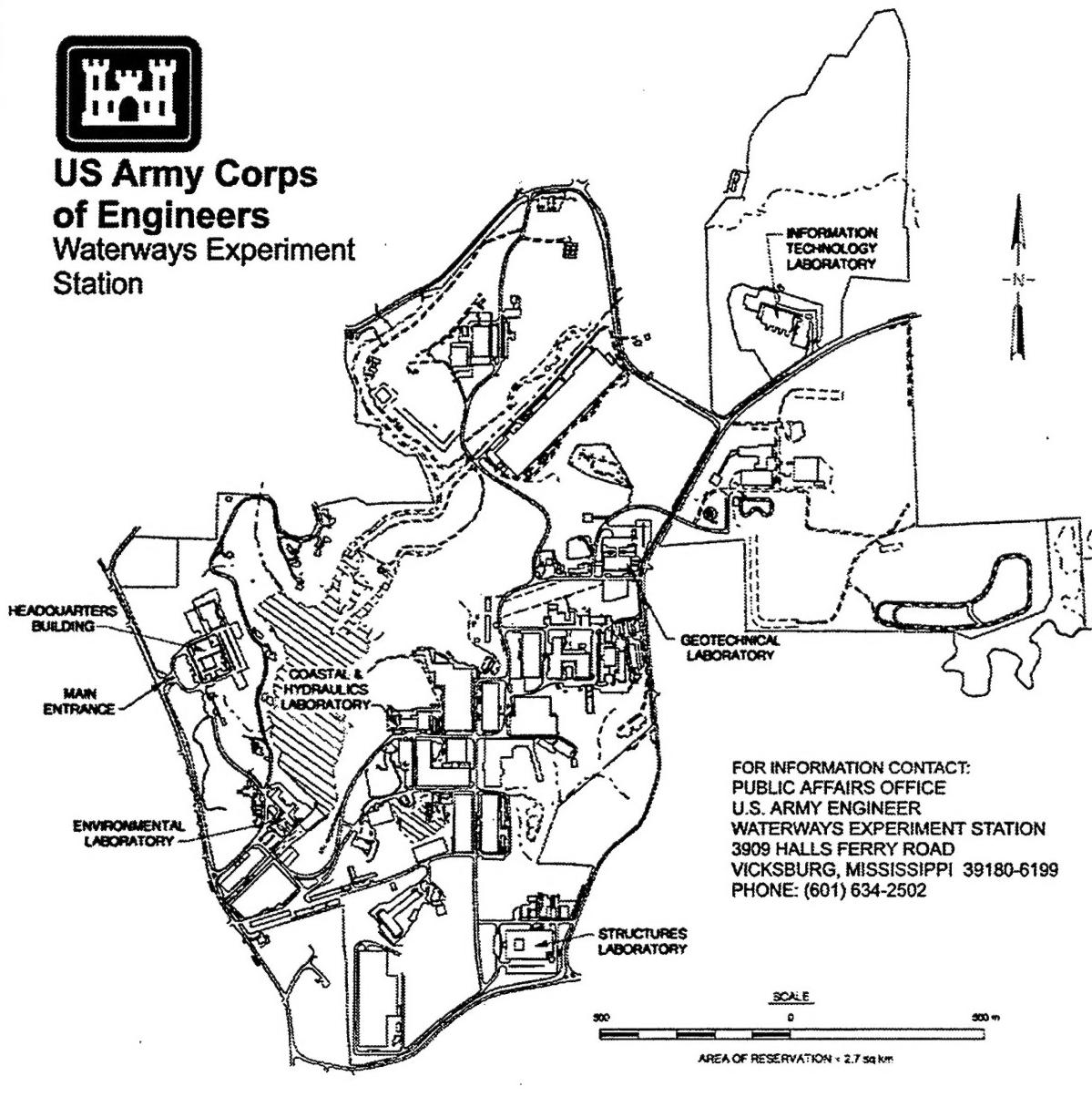
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Bioengineering for Streambank Erosion Control; Report 1, Guidelines (TR EL-97-8)

ISSUE: The U.S. Army Corps of Engineers is often restricted from using hard structures, such as riprap or concrete-lined channels, for streambank erosion control because of environmental reasons or high cost. Bioengineering is the combination of biological, mechanical, and ecological concepts to control erosion and stabilize soil through the use of vegetation or a combination of it and construction materials. Both living and nonliving plants can be used. Nonliving plants are used as construction materials, similar to engineered materials. Planted vegetation controls erosion and serves as good wildlife and fisheries habitat in riparian systems. Guidelines are generally lacking for use of bioengineering treatment on streambanks, which often explains why bioengineering is not used more often.

RESEARCH OBJECTIVE: This investigation documents successful bioengineering attempts in Europe and the United States by surveying the literature, relating personal observations in Europe and the United States by the authors, and by monitoring recently applied bioengineering treatments on several stream systems in various parts of the United States. Several case studies where treatments were installed and monitored appear in Report 2. Examples of other treatments at various locations are related in Report 1. Attempts were made, where possible, to document local flow velocities and average stream velocities to which treatments were applied. Thus, an empirical way of approximating some tolerance thresholds is presented that will aid designers in choosing appropriate treatments.

SUMMARY: This study provides guidelines for using bioengineering treatments in a prudent manner while

tempering their widespread use with precautions. Precautions consist of properly designing bioengineering projects with enough hardness to prevent both undercutting the streambank toe and erosion of the upper and lower ends (flanking) of the treated project reach. This can be accomplished with one or both of (a) hard toe and flanking protection, e.g., rock riprap, refusals, and (b) deflection of water away from the target reach to be protected through deflection structures, e.g., groins, hard points, and dikes. With both of these methods, appropriate plant species should be used in a manner consistent with their natural habitats, that is, in an effort to emulate natural conditions or processes. This is often done with streambank zones that more or less correspond with microhabitats of native plant species in local stream environments. Where possible, both herbaceous and woody species are used with grass or grass-like plants in the lowermost zone that is planted; shrubby, woody vegetation is used in the middle zone; and, for the most part, larger shrubs and trees are established in the uppermost zone. These zones are respectively called the "splash, bank, and terrace zones."

AVAILABILITY: The report is available on Interlibrary Loan Service from the U.S. Army Engineer Waterways Experiment Station (WES) Library, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199; telephone (601) 634-2355. To purchase a copy, call the National Technical Information Service (NTIS) at (703) 487-4650. For help in identifying a title for sale, call (703) 487-4780. NTIS numbers may also be requested from the WES librarians.

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Preface

The work described herein was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Environmental Impact Research Program (EIRP). The work was performed under Work Unit 32830, Bioengineering for Streambank Erosion Control. Messrs. Hollis H. Allen and James R. Leech, Environmental (EL) and Coastal and Hydraulics (CHL) Laboratories, respectively, of the U.S. Army Engineer Waterways Experiment Station (WES), were the Principal Investigators of this work unit. Ms. Cheryl Smith and Messrs. Frederick B. Juhle and Forrester Einersen were the HQUSACE Program Monitors for this work.

Mr. Dave Mathis was the EIRP Coordinator at the Directorate of Research and Development, HQUSACE. Dr. Russell F. Theriot, WES, was the EIRP Program Manager.

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The report was written by Messrs. Allen and Leech under the direct supervision of Dr. Michael F. Passmore, Chief, Stewardship Branch, EL, and under the general supervision of Dr. Robert M. Engler, Chief, Natural

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or kelvins ¹
feet	0.3048	meters
inches	2.54	centimeters
pounds (mass)	0.4535924	kilograms
quarts (U.S. liquid)	0.9463529	liters
tons (2,000 pounds, mass)	907.1847	kilograms

¹ To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F-32)$. To obtain kelvin (K) readings, use the following formula: $K = (5/9)(F-32) + 273.15$.

1 Introduction

Background

The U.S. Army Corps of Engineers (CE) and others are often restricted from using hard structures, such as riprap or concrete-lined channels, for streambank erosion control partly because of environmental reasons and high cost. Within the last decade or so, increased demands have been placed upon the CE by environmental agencies and others to incorporate vegetation into their streambank erosion control projects rather than to rely completely on traditional methods. Complete bank armorment by various methods such as riprapped revetment, concrete revetment, bulkheads, concrete linings, etc., are considered by many to have little value for fisheries, wildlife, water quality, and aesthetic appeal. Bioengineering, in contrast, is receiving more emphasis from environmental agencies and conservation organizations. Bioengineering is the combination of biological, mechanical, and ecological concepts to control erosion and stabilize soil through the sole use of vegetation or in combination with construction materials. Both living and nonliving plants can be used. Nonliving plants are used as construction materials, similar to engineered materials. The planted vegetation controls erosion and serves as good wildlife and fisheries habitat in riparian systems.

A limited number of streambank erosion control projects have been designed and implemented by the CE where bioengineering has been purposely planned as a part of the project. The CE has historically relied on construction projects with design lives of 50 to 100 years that require a minimum amount of maintenance. Therefore, the focus of development has been on hard structures that can be modeled and studied in hydraulic flumes and other test structures and are designed to stay in place a long time. The CE has been reluctant to design softer treatments, e.g., bioengineering, for erosion control because of a lack of specific design guidance. For instance, under what velocity conditions will certain vegetative treatments work? This type of information has been slow to develop. In part, a lack of monitoring after streambanks have been treated with a vegetative method has led to unknown performance conditions and failure thresholds. In 1993, efforts were taken under the purview of the Environmental Impact Research Program (EIRP), sponsored by Headquarters, U.S. Army Corps of Engineers, to develop and demonstrate bioengineering concepts for streambank erosion control and to determine hydraulic velocities and conditions for successful prototype performance and use.

Purpose

This report synthesizes information related to bioengineering applications and provides preliminary planning and design guidelines for use of bioengineering treatments on eroded streambanks. It can be used by both planning and design elements, not as a cookbook, but as a guide with tools to accomplish bioengineering projects. It presents a bioengineering design model with examples in the text that describe specific case studies where certain stream conditions, such as velocities, have been provided. It also describes appropriate plants to use, their acquisition, and their handling requirements.

This study is divided into two reports. The main report, Report 1, provides bioengineering guidelines for streambank erosion control. Report 2 presents several case studies of bioengineering treatments applied to one or more streams in various geographic locations around the continental United States.

Scope

The authors of this report do not attempt to assume that bioengineering for streambank protection is a cure unto itself. First, bed stability, another whole subject area, must be achieved before banks are addressed. If streambeds are not stable, it does little good to attempt bank stabilization. This report does not attempt to address the details of fluvial geomorphology, but the authors recognize that bioengineering must be done in consonance with good riverbed and planform stability design; there are several texts and engineer manuals that address these subjects. Consequently, good bioengineering takes an interdisciplinary team approach with expertise representing engineering, physical, and biological fields, as well as others, a point reemphasized throughout this report. The authors also recognize that causes of streambank erosion are complex and can often be related to land-use practices being conducted in the watershed and/or in the immediate vicinity of the erosion problem on the streambank. Therefore, careful study should be made of the causes of erosion before bioengineering is contemplated. Again, an interdisciplinary team is often required to develop an optimum plan. Bioengineering must be done within the context of a landscape approach, but erosion control must be addressed by reaches, from a practical standpoint. The report provides a planning sequence, or bioengineering design model, that is tailored to a zonal approach within reaches.

Vegetation, per se, is not a panacea for controlling erosion and must be considered in light of site-specific characteristics. When vegetation is combined with low-cost building materials or engineered structures, numerous techniques can be created for streambank erosion control. This report summarizes a number of techniques that utilize vegetation. For understanding how vegetation can be used in bioengineering and as a basis for conceptualizing a bioengineering design model, it is important to understand both the assets and limitations of using planted vegetation.

Assets of using planted vegetation

Gray (1977), Bailey and Copeland (1961), and Allen (1978) discuss five mechanisms through which vegetation can aid erosion control: reinforce soil through roots (Gray 1977); dampen waves or dissipate wave energy; intercept water; enhance water infiltration; and deplete soil water by uptake and transpiration. Klingeman and Bradley (1976) point out four specific ways vegetation can protect streambanks. First, the root system helps hold the soil together and increases the overall bank stability by its binding network structure, i.e., the ability of roots to hold soil particles together. Second, the exposed vegetation (stalks, stems, branches, and foliage) can increase the resistance to flow and reduce the local flow velocities, causing the flow to dissipate energy against the deforming plant rather than the soil. Third, the vegetation acts as a buffer against the abrasive effect of transported materials. Fourth, close-growing vegetation can induce sediment deposition by causing zones of slow velocity and low shear stress near the bank, allowing coarse sediments to deposit. Vegetation is also often less expensive than most structural methods; it improves the conditions for fisheries and wildlife, improves water quality, and can protect cultural/archeological resources.

Limitations of using planted vegetation

Using planted vegetation for streambank erosion control also has limitations. These may include its occasional failure to grow; it is subject to undermining; it may be uprooted by wind, water, and the freezing and thawing of ice; wildlife or livestock may feed upon and depredate it; and it may require some maintenance. Most of these limitations, such as undermining, uprooting by freezing and thawing, etc., can often be lessened or prevented by use of bioengineering measures.

2 Bioengineering Design Model

A conceptual design model is offered below that leads one through the steps of planning and implementing a bioengineering project. It draws largely upon similar thought processes presented by Leiser (1992) for use of vegetation and engineered structures for slope protection and erosion control. Where appropriate, the report will reference examples in the main text (Report 1) and case studies (Report 2) that describe particular bioengineering treatments on selected and monitored stream systems. The model includes planning and its associated components that will be defined below; use of hard structures and bioengineering; a vegetative zonal concept; and various bioengineering fixes by zone. Monitoring, follow-up, and care should naturally follow.

Planning

A bioengineering project may be primarily desired for erosion control, but often there are other considerations. Thought should be given to important functions that the bioengineering treatment can perform, such as habitat development, archeological site protection, water quality improvement, aesthetics, or a combination of these. The political and economical requirements or constraints of implementing any project must be considered. Any bioengineering streambank stabilization project should be planned within the context of the landscape in which the stream is located. Additionally, the bioengineering work cannot be accomplished without determining the upstream, downstream, and cross-stream impacts. Any action on a stream results in a reaction. The bioengineering project may direct flows toward the adjacent property owner or includes fill that raises the water surface on opposite bank property. These considerations must be taken into account. Activities near the stream that is influencing its erosion must be identified. It is a wasted effort to install bioengineering treatments in an area where cattle are allowed access to the treated reach immediately after construction. The stream must be examined as a system, but the restoration must be accomplished at the reach level from a practical perspective. The planning part of the model should address potential functions of the treatment and the political and economical concerns (Figure 1).

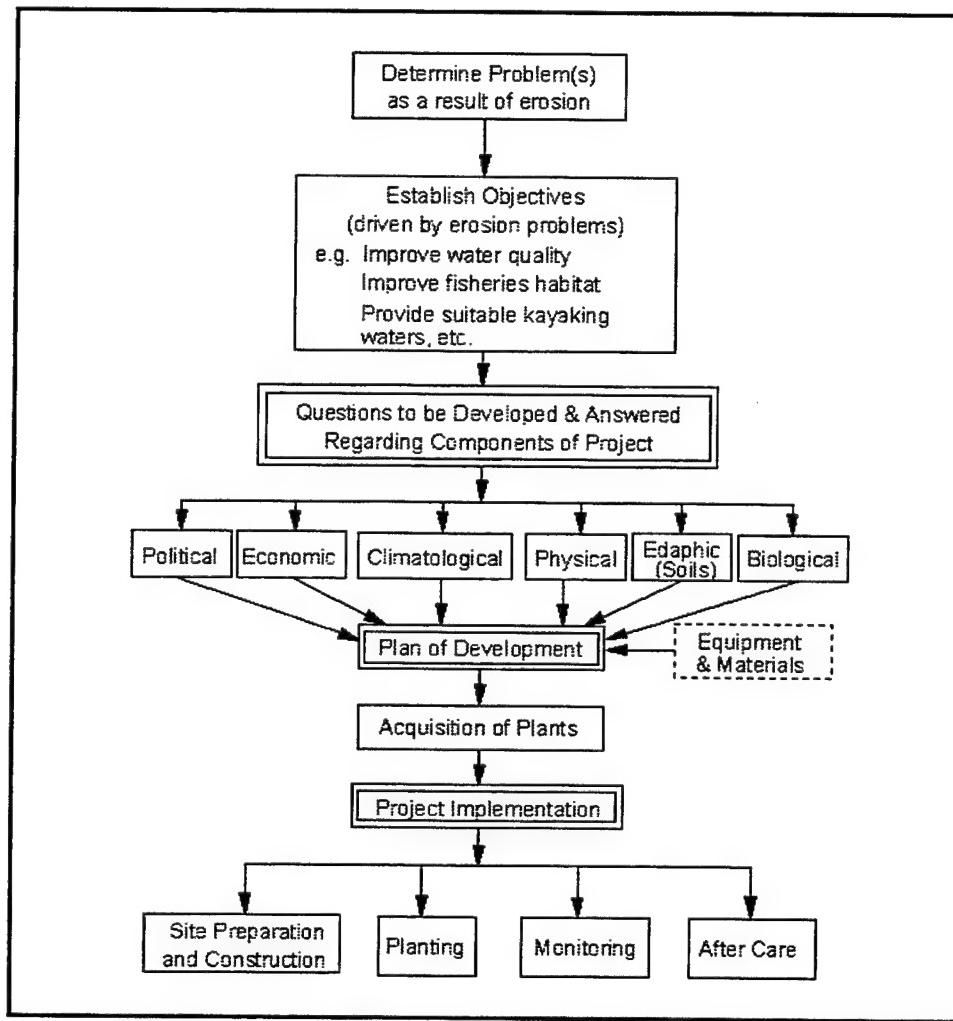


Figure 1. Steps of planning and implementing a bioengineering project

Determine problem(s) and establish objectives

Clear-cut objectives that are based on some perceived problem or problems are needed for any project. The problem or problems may be results of erosion, such as poor water quality, lack of fisheries, lack of suitable water for kayaks, and others. The objectives are then driven by these and may relate to primarily erosion control, but may also include providing fisheries or wildlife habitat, improving water quality, protection of cultural resources, or a host of other desired functions. Bowers (1992) established objectives on the Little Patuxent River, Maryland, that included not only erosion control, but also in-stream and riparian habitat enhancement. These objectives are often driven not only by the physical impacts of erosion on the landscape, but by legal mandates, such as mitigation for some action on the stream. Questions must be asked and answers provided before the project can proceed. This effort will require that an interdisciplinary team be developed consisting minimally of engineers, hydrologists, and life scientists with expertise in bioengineering approaches. Other disciplines, such as economists, sociologists, and attorneys can be consulted as needed during the planning stage of development.

Questions to be developed and answered

Any streambank erosion control project has several components. Each component may have constraints that have to be overcome. These components with associated constraints are interdependent and must be considered, thus generating an abundance of questions that should be answered, if possible. They include the political, economic, climatological, physical, edaphic (soils), and biological components of the project. Both the asking and answering of these questions relative to these components lead to the Plan of Development. Once the plan is developed and permits acquired, procurement of plants will be required (See Chapter 3). After or concurrent with this procurement, implementation of the plan can proceed. The political component includes governmental regulations, such as those presented in Section 404 of the the Clean Water Act (formerly known as the Federal Water Pollution Control Act, 33 U.S.C. 1344). It also includes public pressures, such as restricting bioengineering to the use of only native plant species or plants that are grown in a nursery as opposed to those harvested from the wild. Governmental regulations and/or public pressures may also mandate that certain vegetation species or types of species be used. If a certain species blocks the view of a river in an urban setting, for instance, public pressures may cause plans to change to use a different species or a different erosion control treatment altogether. Lack of grazing controls, limitations on use of chemicals for rodent, insect, or weed control or fertilizers are other examples of these constraints and must be considered in any bioengineering design criteria protocol. The political component also includes the negative human factors of vandalism and trespass by foot and off-road vehicles, as well as the positive factor of public pressure for improvement of the environment.

The economic component could be one of the more important factors to enable bioengineering erosion control efforts. Usually, bioengineering projects are less expensive than traditional engineering approaches. However, economics invariably affects the final decisions on the selection of plant species and planting densities, as well as preproject experimentation and aftercare activities. A bioengineering design protocol must include funding for monitoring and allow for remedial planting and management of the site to meet the objectives of the project. Bioengineering projects will often require more funds early in the project's history for possible repair and assurance of effectiveness than traditional engineering, but will be more self-sustaining and resilient over the long term. If traditional engineering projects need remediation over the life of the project (and they frequently do), the remediation occurs later in the life of the project but with higher overall costs.

The climatological component includes several aspects of a project site: rainfall (amount and distribution), temperature (heat and cold, time, duration, and intensity), humidity, day length, etc. Climatological components affect plant species selection, how those plants will be planted, and treatment after planting. With some exceptions, bioengineering projects in humid regions with ample rainfall and projects along permanent flowing streams will probably require less effort to establish vegetation than those along intermittent flowing streams in dry climates. In desert climates, where fewer plants in the inventory can be chosen than in humid climates, learning these plants' life requisites is essential for successful planting.

The probability for bioengineering project failure is higher with fewer species planted and where growth stresses are greater.

The physical component includes physical parameters of a project: site stability such as subsidence or accretion; aspect (direction slope faces), which in turn influences environmental factors such as temperature (south- and southwest-facing sites are hotter, and evapotranspiration is higher than in other directions); hydrodynamic aspects such as water sources (groundwater, surface water) and water frequency, timing, depth, duration, and flooding relationship to bank height; fluvial geomorphology such as historical stream meander, pattern, cross-sectional, and longitudinal profiles and energy sources such as wave and current action; and geomorphic features such as landforms and terrain influences, e.g., impacts of offsite water sources.

From the above list of physical parameters, hydrologic and geomorphic factors are particularly important. For purposes of determining where to use vegetation on the bank and the kinds of vegetation to use and when to plant, one needs a knowledge of the stream's hydrographic and fluvial geomorphic characteristics. If stream gauge data are not available, one will have to rely on high water marks, the knowledge of persons living in the areas, and any other data derived from local vegetation and soils that indicate flood periodicity. Table 1 gives an example of hydrologic characteristics of the upper Missouri River. It shows the frequency of various flows and their duration with 25,000 cfs¹ being the normal flow from late spring through fall. A 40,000-cfs flow with a duration of 6 months can be expected to occur once every 10 years. Figure 2 subsequently shows the approximate water level corresponding to various river flows using the level of 25,000 cfs as the reference. At a flow of 40,000 cfs, the river

Table 1
Recurrence Interval by Discharge and Duration on Upper
Missouri River¹

Discharge, cfs	Duration			% Probability of Not Occurring (60 Days)
	6 Months	60 Days	1 Day	
60,000	—	1/100 years	1/20 years	99
50,000	1/100	1/10	1/5	90
40,000	1/10	1/3	1/2	67
35,000	1/3	1/2	1	50
30,000	1/2	1	1	1
25,000	1	—	—	—

¹ A table of factors for converting non-SI units of measurement to SI units is presented on page xii.

level will be approximately 3 ft above the reference level. From other data, one also knows that flows exceed normal usually in June or July; therefore, planting should occur in early spring or fall.

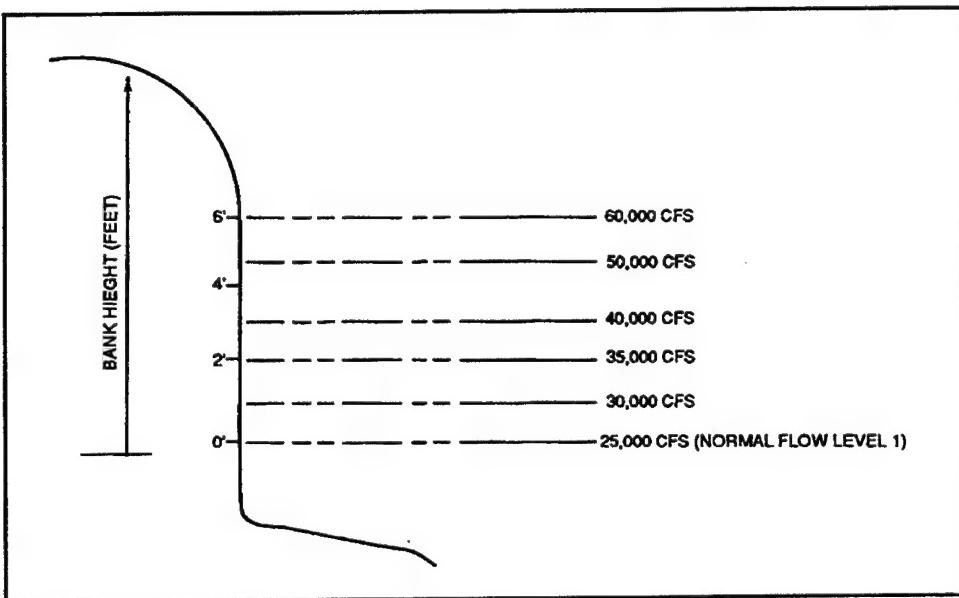


Figure 2. River levels and flows of upper Missouri River below Garrison Dam

These data also give information that leads to forming vegetation planting zones. One knows that for this example, a daily high flow of 35,000 cfs translates to a zone 2-ft high on the bank that could occur once for 60 days every 2 years. This means that this zone will have to be vegetated with extremely flood-tolerant vegetation, e.g., emergent aquatic species, willow (*Salix spp.*), and is equivalent to a "splash zone" that will be discussed later.

Geomorphic characteristics such as bank geometry play a major part in the employment of bioengineering. Banks that have been eroded and undercut to a very steep, unplantable slope require grading prior to planting (Edminster, Atkinson, and McIntyre 1949; Edminster 1949). The angle required varies with the soil, equipment used, and several other factors. Sand, for instance, has an angle of repose of about 30 deg, whereas clay can stand on a much steeper angle (Gray 1977). Most slopes that accommodate revegetation are less than 1-1.2 V:1 H. On steep banks where undercutting may be a problem, the toe of the bank may need protecting with riprap or other hard, structural treatments. Special structural treatments other than vegetation and drainage structures may be necessary where geomorphic features contribute to internal erosion of the bank, called piping or sapping. This is where water can seep into the bank from higher elevations through porous strata and cause bank failure when the erodible strata are gone. Sometimes, bioengineering with appropriate geotextile filters can treat piping problems, but not always.

The edaphic component includes all the soil parameters: texture, structure, fertility, erodability, chemistry, etc. Soil texture, structure, and depth

all affect the water holding capacity of a soil and need to be considered when determining water retention requirements or supplemental irrigation requirements during dry periods of the year. In addition to ensuring proper bank slopes and bank toe protection, attention should be given to the edaphic component that may in turn require some site preparation activities. It is desirable to have slopes covered with at least a 10-cm layer of topsoil high in organic matter; this can be stockpiled prior to any grading. Movement of soil, however, is expensive and must be considered in light of the economic practicality. In lieu of moving rich topsoil, the existing substrate may be amended with fertilizer and mulch to help produce a better soil. In any case, plants need a growing medium that supports the plant and facilitates nutrient and water uptake. The site may require other soil amendments such as lime, gypsum, or other special nutrients depending upon the soil's pH and fertility. Soil tests should be conducted prior to revegetation to determine any amendments needed.

The biological component is one of the most important components and is interdependent with the other components. It includes habitat requirements of animal and plant species and the plan can be modified to some extent to meet these requirements if the life requisites of these species are known. This component also includes the availability of suitable plant species that, in part, make up the habitat for various riparian animals. Choices must be made between native and introduced species, plants obtained from commercial nurseries, or from the wild. This component also includes the propagation and cultural practice for the plants, planting, and aftercare. It includes plant diseases, insects, predators, and the presence or absence of grazing animals. An example of spider mite damage is presented in the case study of Court Creek, Illinois, Report 2, where willow had to be sprayed with an insecticide to control damage. If spraying had not occurred, streambank protection with living willow would not have been achieved. Protective screen sleeves or deer and grazing animal exclosures must be provided if these risks are present. The potential for damage from insect, rodent, deer, and other predation must be considered and protection provided to planted wetland vegetation.

The biological attributes of an area containing a bioengineering site are very important and plants are no exception. They are there because they have adapted to the ecological conditions of the area, such as climate, soils, etc. To use bioengineering effectively, one should learn to identify and evaluate plants that are growing in the area that have become adapted. These should include plants that are growing along all parts of the streambank, lower, middle, and upper. In bioengineering, these conditions and species should be emulated as much as possible. Native plants or plants that have become naturalized in the area should normally be used. Exotic plants should be avoided since there are species that may get out of control and become nuisances. One only has to look at examples such as purple loosestrife (*Lythrum salicaria*) to gain an appreciation of the problems exotic plants can cause.

Plants chosen should have some tolerance to flooding. Some will need to be highly tolerant (those planted lower on the bank) while others (those planted higher on the bank) can be less tolerant. Plants chosen also will have to withstand some dry conditions as well as flooded conditions because of the fluctuating nature of water levels in streams.

A mixture of grasses, herbs, shrubs, and trees should be used, if possible, to provide a diversity of wildlife habitats. Some legumes such as yellow sweet clover (*Melilotus officinalis*), white sweet clover (*M. alba*), and crownvetch (*Coronilla varia*) are possible choices because of their nitrogen-fixing attributes. These, however, should be used at an elevation subject to only intermittent and short periods of flooding, such as in the upper bank and terrace zones discussed below.

Plan of development

The plan of development is the culmination of answering all the questions in the various categories mentioned above. Many of the questions regarding the above components can be answered offsite, but a site analysis is mandatory before plants can be procured or before project implementation can occur. In the site analysis, each component must again be examined to include the various factors or parameters and what will influence vegetation development for bioengineering and the stability of a streambank. A general guideline for the site analysis is to be a keen observer as to the conditions occurring at the project reach as well as upstream and downstream from it. From observations of a reference site, many answers can be found about what kinds of plants to use, invader species that are apt to occur, causes of problems, such as overgrazing, road construction upstream contributing to a high bed load of sediment, etc. The same or similar plant species that occur at the reference site should be acquired. In a site analysis, much of the data from a reference streambank area can be taken to answer the questions posed.

Equipment and materials

In the plan of development, consideration should be given to the equipment and materials required for vegetation handling and planting at the implementation stage. The tools required and the planting techniques will depend on the type of vegetation, i.e., woody or herbaceous, the size of plants, soils, and the size of the project and site conditions. Freshwater herbaceous plantings with low-wave or current-energy environments may call for tools like spades, shovels, and buckets. In contrast, high-energy environments of waves and currents may require tools for bioengineering installations. Such tools include chain saws, lopping and hand pruners for the preparation of woody cuttings, and materials for woody bioengineering methods; or heavy hammers and sledges for driving stakes in bioengineering treatments such as wattling and brush matting. Specialized equipment may be required. This is true when moving sod or mulches containing wetland plants or plant propagules. It is also true since bioengineering projects often have the constraints of working in a pristine stream system where riparian corridors are extremely valuable, particularly in large, urban settings. It is in these settings that equipment size and type constraints are often placed upon the project. Thus, downsized front-end loaders and walking excavators are sometimes required to minimize disturbance of existing vegetation and soil. Other equipment and materials may include fertilizers, soil amendments, (e.g., lime), fencing for plant protection, and irrigation equipment for keeping plants alive during dry conditions. Other

equipment and materials for keeping plants alive before they are planted may include shading materials such as tarps, buckets with water for holding plants, and water pumps and hoses for watering or water trucks.

Permit acquisition

After the site analysis and bioengineering actions are determined, necessary permits must be obtained, such as those governing any action impacting wetlands, water quality, cultural/historical resources, threatened and endangered species, and navigation. Usually and especially on smaller streams not requiring large structures or bank shaping as a part of the design, the permit process will not be very complex or time-consuming. However, on large streams where deflection structures are employed or where banks are extensively shaped, navigation, cultural resource, and wetland permits can take several months to acquire. Depending on the size and complexity of the project, National Environmental Protection Act compliance documents may also be required.

Acquisition of plants

Prior to the implementation of the project, the plans for acquiring plants must be made well in advance (sometimes 1-2 years). To select vegetation for the project, vegetation existing on or near a site and on similar nearby areas which have revegetated naturally are the best indicators of the plant species to use. If commercial plant sources are not available (U.S. Department of Agriculture (USDA) Soil Conservation Service 1992), then onsite or offsite harvesting can be considered. When acquiring plants, care must be given to local or Federal laws prohibiting such plant acquisition and decimating the natural stands of wetland plants. Additionally, care must be taken to ensure that pest species, such as purple loosestrife, are not collected and transferred to the project site.

The availability of plants of the appropriate species, size, and quality is often a limiting factor in the final selection and plant acquisition process. Some native plant species are very difficult to propagate and grow, and many desirable species are not commonly available in commerce or not available as good quality plants. As demand increases and nurserymen gain more experience in growing native plant species, this limitation should become less important (Leiser 1992). Plant species composition and quantity can often be determined from the project objectives and functions desired. As a general rule, it is advisable to specify as many species as possible and require the use of some minimum number of these species. Maximum and minimum numbers of any one species may be specified. See Chapter 3 for additional information on plant acquisition, times of planting, and plant-handling techniques.

Implementation

Implementation is the natural follow-up to the plan of development and is integrated with the planning process. It should not be separated from it.

It is the final stage of the conceptual and detailed design but may require feedback into design plan formulation for possible onsite corrections. It includes site preparation and construction, planting, monitoring, and after-care. For the bioengineering design to be successful, it must have close supervision throughout by someone familiar with implementation of bioengineering projects. This stage requires close attention to detail. It is important in this stage to maintain continuity of the same interdisciplinary team who planned and designed the project and keep them involved in this part of the project. Those capable of actually carrying out the project should be a team of persons with knowledge and experience of both stream morphology and mechanics, hydraulic and geotechnical engineering, and bioengineering. Regarding vegetation, the person should possess both training and experience in wetlands plant science and development. It is mandatory that the person be onsite intermittently at least during project construction and especially planting. All of the efforts to address the various components of design will be in vain unless plants are handled and cared for properly when planted and even after planting in many cases.

Planting techniques

There are several planting techniques for bioengineering ranging from simple digging with shovels or spades and inserting sprigs (rooted stems) or cuttings to moving large pieces of rooted material, such as sod, mulch, and root pads (large rooted shrubs). Other methods consist of direct seeding, hydroseeding, or drilling individual seeds such as acorns of wetland oak species. All of the above methods capitalize on combining the attributes of plants with some kind of engineered material or structure or relying on the plant itself to form a resistant structure to erosion, such as a live willow post revetment. Various techniques will be discussed in detail below.

Monitoring and aftercare

Most importantly, monitoring and necessary aftercare must be a part of any bioengineering design and must be included in the plan of development and the implementation stage. The intensity and frequency of monitoring and aftercare will depend on site conditions, such as harshness of climate, probability of animal disturbance, high-wave or current conditions, etc., and on established success criteria.

On many sites, it is essential to protect plantings from damage by animals, such as Canada geese (*Branta canadensis*) or beaver (*Casta canadensis*) and other mammals. The use of irrigation may be required during aftercare and will improve growth and survival of plantings that are installed during dry seasons and in dry soils. The decision about irrigation must be made based on economics contrasting the need to irrigate with the cost of possible mortality and the consequences of failing to obtain the desired erosion control and other functions. See Chapter 4 for more detail on monitoring.

Hard Structures and Bioengineering

Generally speaking, bioengineering is considered "a soft fix." This is not necessarily the case. On first or second order streams, the sole use of vegetation with perhaps a little wire and a few stakes for holding the vegetation until it is established makes bioengineering more of a soft treatment. However, bioengineering is used also in combination with hard structures. These hard structures are used to protect the toe of the bank from undercutting and the flanks (ends of treatment) from eroding. The larger the stream or stronger the flow, the more probable that hard structures will be incorporated into the bioengineering design model. This is also true when risks become greater, such as when an expensive facility is being threatened. As an example, a utility tower along a stream in Georgia¹ was being threatened by erosion. A rock revetment had previously been used in front of the tower, but was washed out. A bioengineering treatment that incorporated live willow whips and a log crib were installed to control erosion. Crib logs controlled undercutting and flanking while the live willow whips installed between the log stringers developed and strengthened the overall structure and gave it a "green" appearance.

In most of the case studies presented in Report 2, and in the references made to other bioengineering streambank erosion control, hard structures such as rock riprap, log/tree revetments, tree butts, and deflection dikes were used to protect toes from being undercut or flanks at the upper and lower ends from being washed out. In these cases, water currents are prevented from undercutting the bank either through direct protection of the lower bank with some hard structure or material or through some kind of deflection structure that deflects the currents off the bank. Deflection structures may be some kind of spur dike, vane, transverse dike, or bend-way weir. Figure 3 shows two timber cribs serving as deflection structures on the upper Missouri River to direct current away from the bank. In the case of hard toes on the lower bank, plants and engineered materials to hold them in place are positioned above the hard toe. Rock riprap keyed into the bank at both the upper and lower ends of a bioengineering treatment are called refusals (Figure 4) and prevent currents from getting behind the structure, called flanking. In the case of a deflection structure, these are usually placed in a series at critical points of scour, and plants with engineered materials are placed in between them to help hold the bank. With the aid of these structures and time, the planted vegetation establishes roots and stems in the bank to hold it together and trap sediment. This sedimentation, in turn, leads to spread of the planted species and colonization by other opportunistic plants.

¹ Personal Communication, 1996, Ms. Robin Sotir, President, Robin Sotir and Associates, Marietta, GA.

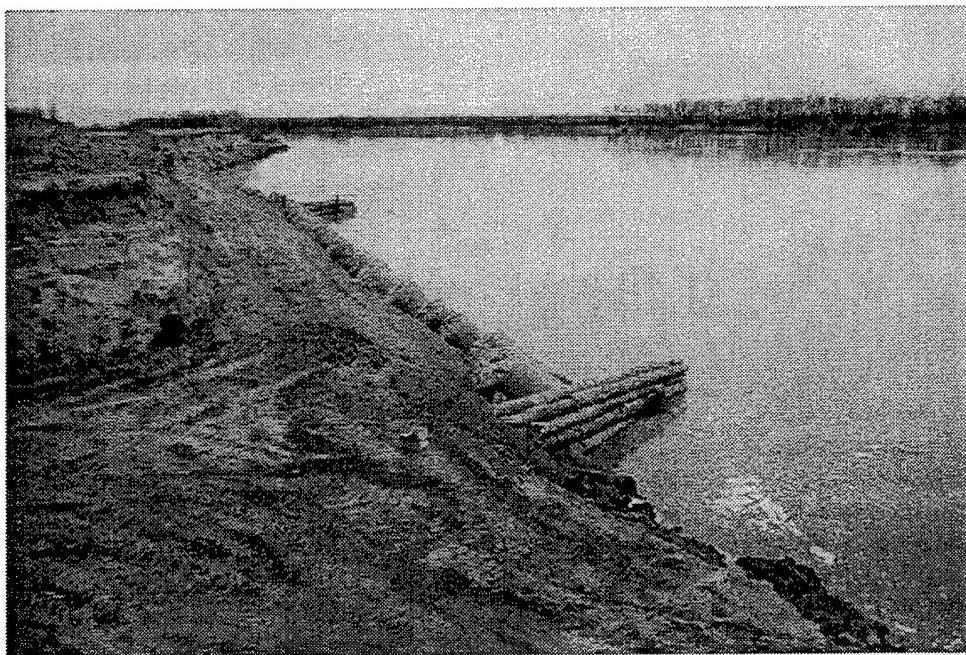


Figure 3. Timber cribs serving as deflection structures on upper Missouri River to direct current away from bank where there are bio-engineering treatments

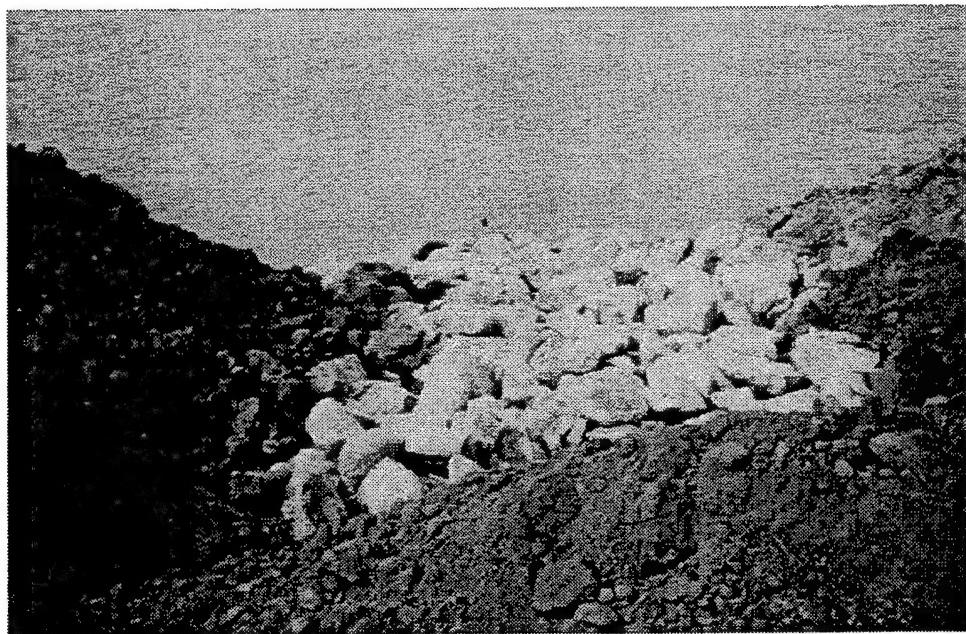


Figure 4. Rock refusal used on an upper Missouri River bioengineering project (Note that it is keyed back into bank to prevent flanking of upper and lower end sections of project)

Bioengineering by Zones

Plants should be positioned in various elevational zones of the bank based on their ability to tolerate certain frequencies and durations of flooding and their attributes of dissipating current and wave energies. Likewise, bioengineering fixes should be arranged by zone, which will be discussed below. The zone definitions given below correspond to those used by the U.S. Army Engineer District, Omaha, and have been used in preparing guidelines for the use of vegetation in streambank erosion control of the upper Missouri River (Logan et al. 1979). These zones are not precise and distinct since stream levels vary daily and seasonally—they are only relative and may be visualized as somewhat elastic depending on the bank geometry. If one carefully copied nature in the planning process, plant species can be chosen that will adapt to that specific zone or microhabitat. Mallik and Harun (1993) lend credence to this zonal concept in a study on the Neebing-McIntyre Floodway, parts of the Neebing and McIntyre River Complex near the Intercity area of Thunder Bay, Ontario, Canada. They describe four microhabitats: bank slope, scarp face, above-water bench, and underwater depositional shelf. Each one had distinctively dominant plant species that generally correspond to the types of plants adapted for this report. Figure 5 illustrates the location of each bank zone for the upper Missouri River example. A description of each and the types of vegetation and appropriate species examples associated with them is given below. This zonal concept can be expanded to other streams to facilitate prescription of the erosion control treatment and plants to use at relative locations on the streambank.

Toe zone

The toe zone is that portion of the bank between the bed and average normal stage. This zone is a zone of high stress and can often be undercut by currents. Undercutting here will likely result in bank failure unless preventative or corrective measures are taken. This zone is often flooded greater than 6 months of the year.

Figure 6 illustrates the plant species prescribed for each streambank zone on the upper Missouri River except for the toe zone. The toe zone would likely have to be treated by some hard material, such as rock, stone, log revetments, cribs, or a durable material such as a geotextile roll (to be discussed later).

Splash zone

The splash zone is that portion of the bank between normal high-water and normal low-water flow rates. This and the toe zone are the zones of highest stress. The splash zone is exposed frequently to wave wash, erosive river currents, ice and debris movement, wet-dry cycles, and freezing-thawing cycles. This section of the bank would be inundated throughout most of the year (at least 6 months/year), but note that a large part of this

inundation may occur in the dormant season of plants. The water depths will fluctuate daily, seasonally, and by location within the splash zone.

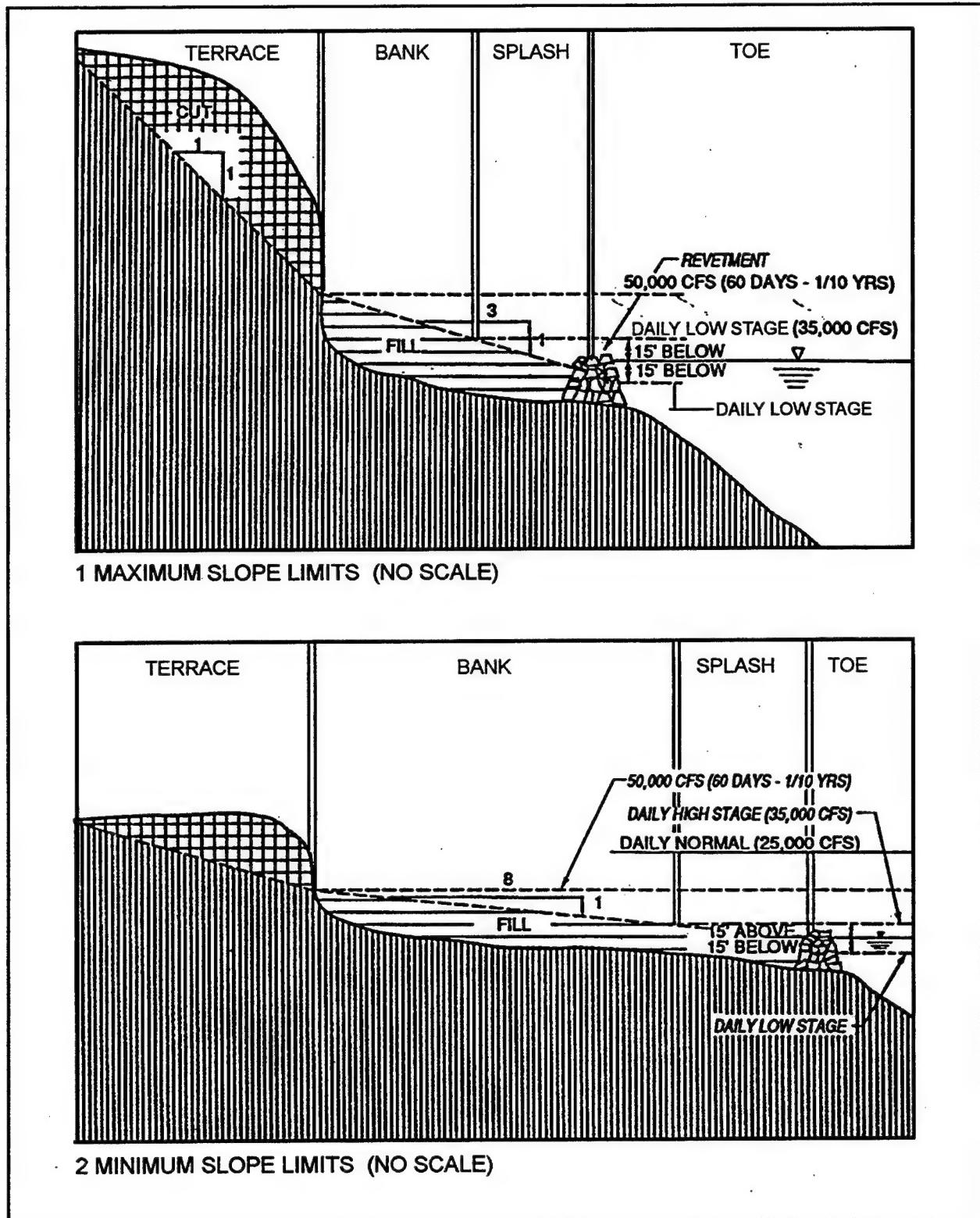


Figure 5. Bank zones defined on constructed slopes

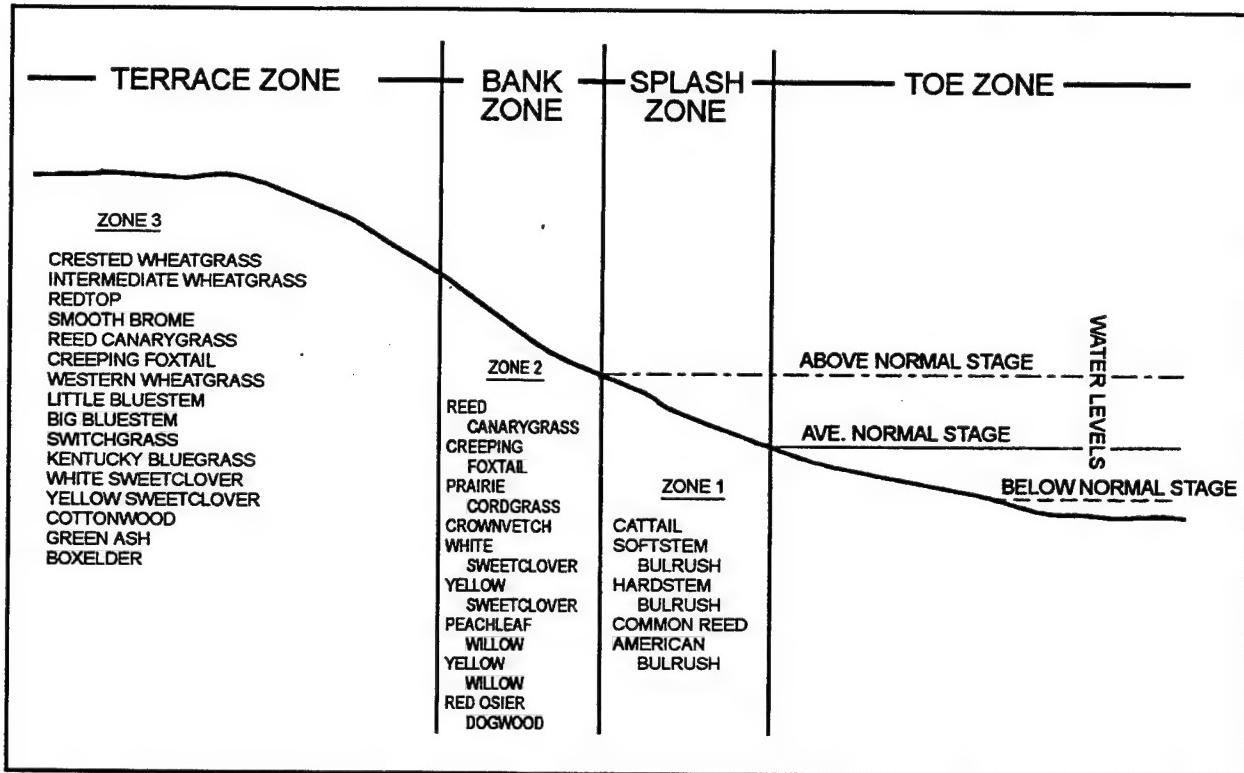


Figure 6. Possible species to plant by zone on Missouri River

Herbaceous emergent aquatic plants like reeds, rushes, and sedges are often planted in the splash zone (Figure 6). These types of plants can tolerate considerable flooding and are more likely to live in this zone. They possess aerenchyma, cells with air spaces, in roots and stems that allow the diffusion of oxygen from the aerial portions of the plant into the roots (Mitsch and Gosselink 1986). Therefore, they can extend roots into deeper water than many other types of plants, such as woody plants. Reeds, such as common reed (*Phragmites australis*), and sedges, such as bulrushes (*Scirpus* spp.), also protect streambanks in various ways. Their roots, rhizomes, and shoots bind the soil under the water, sometimes even above the water (Seibert 1968). In the reed zone, as Seibert (1968) defines it, they form a permeable underwater obstacle that slows down the current and waves by friction, thereby reducing their impact on the soil. Active protection of the bank can be ensured by reeds only in an area that is constantly submerged (Seibert 1968).

Common reed is often considered a pest in the United States where it has been observed as a monotypic plant that does not offer habitat diversity. This is true where there is not much of an elevation and hydrologic gradient. In other words, on shallow flats that become periodically inundated, it can thrive. However, when it is on a shoreline and becomes inundated over about 18 in., it is often replaced by other more water-tolerant species. One should use caution on where this plant is used and match it to one's objectives.

Various wetland grasses, sedges, and other herbs were used in the splash zone as a part of a coir geotextile roll in an urban park setting in Allentown, PA. The main vegetative components of erosion control of the stream embankment are lake sedge (*Carex lacustris*), stubble sedge (*C. stipata*), and woodland bulrush (*Scirpus sylvaticus*). Other minor components used for diversity and color included rice cut-grass (*Leersia oryzoides*), other sedges (*C. lata*, *C. lanuginosa*, *C. hysterina*, and *C. prasina*), softstem bulrush (*Scirpus validus*), blue flag iris (*Iris versicolor*), and monkey flower (*Mimulus ringens*). The latter two species were provided primarily for additional diversity and color.¹ Siegel reported that these plants, along with bioengineering methods such as the coir roll, stabilized a streambank that was subjected to storm events. In fact, the methods were designed to accentuate and enlarge the existing floodplain to act as a buffer zone for floods associated with storms greater than the 25-year event (Siegel 1994). The vegetation list above only gives one example of types of species that were used for erosion control in the splash zone, i.e., flood-tolerant and fast-growing grasses and sedges. Care should be exercised in selecting species that are adapted to the project's geographic area. Local university botanists and USDA Natural Resources Conservation Service (NRCS, formerly Soil Conservation Service) district personnel can be consulted for suitable species.

Herbaceous emergent aquatic plants, like those shown in Figure 6, must be used on a streambank that has a geometric shape conducive to such plants. Caution must be used on streams that have heavy silt loads that could suffocate plants. These plants must grow in fairly shallow water, from +45 to -152 cm (Allen, Pierce, and Van Wormer 1989). Sometimes, it is impossible or impractical to find or shape a stream to match those conditions. Then, flood-tolerant woody plants, like willow (*Salix spp.*), dogwood (*Cornus spp.*), and alder (*Alnus spp.*), are used in the splash zone. Again, a good rule of thumb is to look at the natural system and observe what is growing there and try to duplicate it.

Bank zone

The bank zone is that portion of the bank usually above the normal high-water level; yet, this site is exposed periodically to wave wash, erosive river currents, ice and debris movement, and traffic by animals or man. The site is inundated for at least a 60-day duration once every 2 to 3 years. The water table in this zone frequently is close to the soil surface due to its closeness to the normal river level.

In the bank zone, both herbaceous (i.e., grasses, clovers, some sedges, and other herbs) and woody plants are used. These should still be flood tolerant and able to withstand partial to complete submergence for up to several weeks. Allen and Klimas (1986) list several grass and woody species that can tolerate from 4 to 8 weeks of complete inundation. This list

¹ Unpublished Report, 1994, M. Siegel, "Biotechnical applications for wetland creation and streambank restoration: Utilizing hydrophytic vegetation with fiber-schines for stabilization of a streambank and replicating the ecological functions of a wetland," Lehigh County Conservation District, Allentown, PA.

should not be considered exhaustive, however. Whitlow and Harris (1979) provide a listing of flood-tolerant woody species and a few herbaceous species by geographic area within the United States that can be used in the bank zone.

Skeesick and Sheehan (1992) report on several other herbaceous and woody plants that can withstand tens of feet of inundation over 3 to 4 months in two different reservoir situations in Oregon. These same species are often found along streambanks. Local university botanists and plant material specialists within the NRCS should be consulted when seeking flood-tolerant plants. Various willows can be used in this zone, but they should be shrublike willows such as sandbar willow (*S. exigua*) and basket willow (*S. purpurea* var. *nana*). Edminster, Atkinson, and McIntyre (1949) and Edminster (1949) describe successful use of basket willow for streams and rivers in the Northeast. Shrub-like willow, alder, and dogwood species have been used in Europe successfully (Seibert 1968). Red-osier dogwood (*Cornus stolonifera*) and silky dogwood (*C. amomum*) also have been used in the Northeast (Edminster, Atkinson, and McIntyre 1949; Edminster 1949). Seibert (1968) notes that in periods of high water, the upper branches of such shrubs reduce the speed of the current and thereby the erosive force of the water. The branches of these have great resilience, springing back after currents subside.

Terrace zone

The terrace zone is that portion of the bank inland from the bank zone; it is usually not subjected to erosive action of the river except during occasional flooding. This zone may include only the level area near the crest of the unaltered "high bank" or may include sharply sloping banks on high hills bordering the stream.

The terrace zone is less significant for bank protection because it is less often flooded, but can be easily eroded when it is flooded if vegetation is not present. Vegetation in this zone is extremely important for intercepting floodwaters from overbank flooding, serving to reduce super saturation and decrease weight of unstable banks through evapotranspiration processes and for tying the upper portion of the streambank together with its soil-binding root network. Coppin and Richards (1990) provide a detailed explanation of plant evapotranspiration, but summarize by saying, "Apart from increasing the strength of soil by reducing its moisture content, evapotranspiration by plants reduces the weight of the soil mass. This weight reduction can be important on vegetated slopes where the soil may be potentially unstable."

As denoted in Figure 6, the terrace zone can contain native grasses, herbs, shrubs, and trees that are less flood tolerant than those in the bank zone, but still somewhat flood tolerant. The tree species also become taller and more massive. Trees are noted for their value in stabilizing banks of streams and rivers (Seibert 1968; Leopold and Wolman 1957; Wolman and Leopold 1957; Lindsey et al. 1961; Sigafoos 1964). The trees have much deeper roots than grasses and shrubs and can hold the upper bank together. The banks of some rivers are not eroded for durations

of 100 to 200 years because heavy tree roots bind the alluvium of flood-plains (Leopold and Wolman 1957; Wolman and Leopold 1957; Sigafoos 1964). A combination of trees, shrubs, and grasses in this zone will not only serve as an integrated plant community for erosion control, but will improve wildlife habitat diversity and aesthetic appeal.

Bioengineering Treatments

The entire streambank should be treated to furnish a maximum array of plants capable of providing proper ground cover and root penetration for erosion protection, wildlife habitat, water quality improvement, and many other benefits. At times, the planting sites or zones may be quite narrow in width or difficult to distinguish depending on the geomorphology of the stream. The entire bank in these cases should be treated as a systematic arrangement of plants and treatment practices.

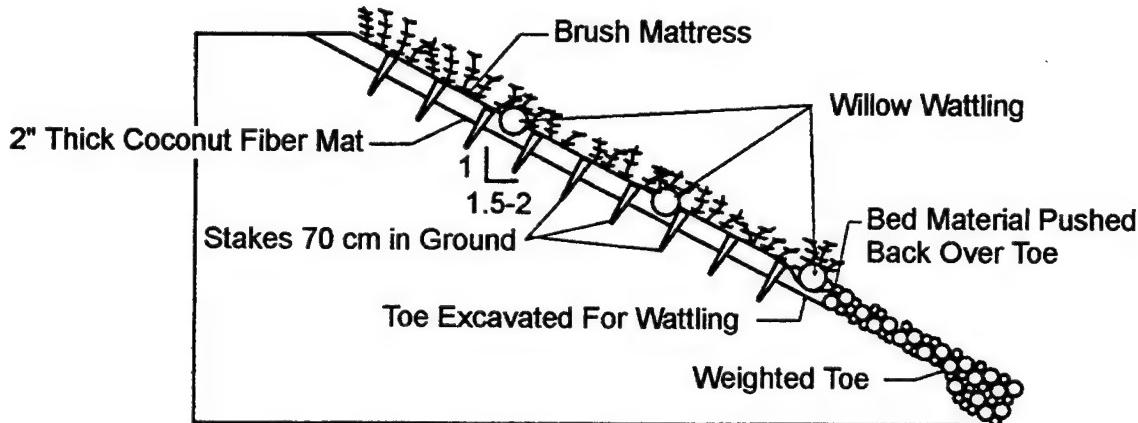
Toe zone

This is the zone that will need to be protected from undercutting with treatments such as stone or rock revetments, gabions, lunkers, log revetments, deflector dikes, cribs, rock and geotextile rolls, root wads, or a combination of materials. The zone rarely has vegetation employed in it alone, but when vegetation is employed, it is used in combination with materials that extend below the normal flow of water and above it. The principle is to keep high-velocity currents from undercutting the bank either through armoring the bank or deflecting the currents away from the site of concern. Vegetation can then be used either above the armor or in between and above the deflecting structure.

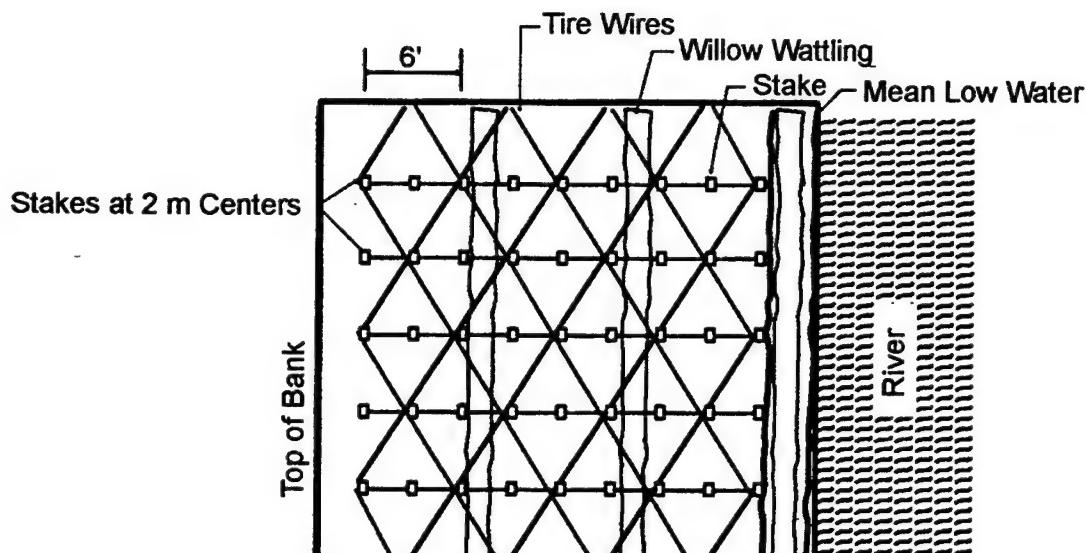
Stone or rock revetments in a bioengineering application are used at the toe in the zone below normal water levels and up to where normal water levels occur. Sometimes, the stone is extended above where normal flow levels occur depending on the frequency and duration of flooding above this level. Then, vegetation is placed above it in a bioengineering application. Stream gauge information helps in making this judgement. Unfortunately, there are no set guidelines for how far up the bank to carry the revetment except to say that it should be applied below the scour zone up to at least the level where water runs the majority of the year. Engineering Manual 1110-2-1601, Change 1 (U.S. Army Corps of Engineers 1994) gives guidelines for riprap toe protection.

One such rock revetment for toe protection was used in conjunction with vegetation above it on Crutcho Creek, Tinker Air Force Base, Oklahoma (Figure 7). In this example, the creek is flashy and often reaches or exceeds the top of bank during the spring of each year for a few days. The rock toe extended from the bed to about one-third the height of the bank (Figure 8). This treatment has been successful in this type of setting after several floods exceeding the top of the bank.

Schematics Of Brush Mattress And Wattling

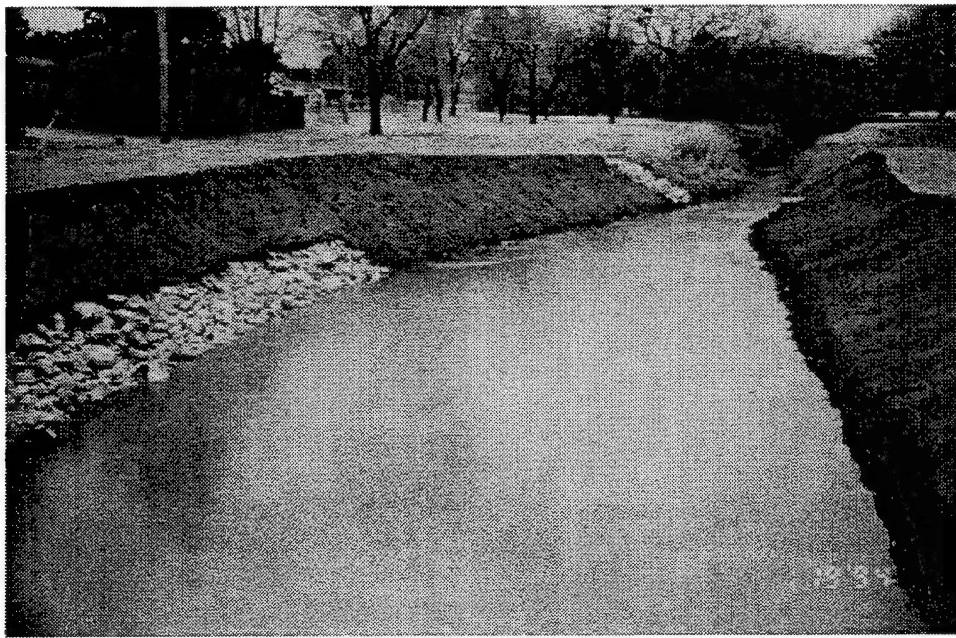


Profile View



Plan View

Figure 7. Schematics of bioengineering treatment used with a weighted rock toe with vegetation in the form of a brush mattress (to be discussed later) used above it



**Figure 8. Photo of weighted rock toe revetment extending up the bank
(Extends about one-third the distance up the bank. Photo shows stream above low-flow conditions)**

Rock toes are also used streamward or just below other materials such as hay bales or geotextile rolls. In one example, the Omaha District recently used rock riprap below a large hay bale cylinder covered with a fabric (rope mesh) made from woven fibers of coconut husks called coir. The riprap weighed about 1.5 tons/ft and was about 3.5 ft deep. Then, vegetation in the form of dormant willow poles (discussed below) was placed above this (Figures 9 and 10).

In another example, a rock roll (Figure 11) was used on the Rhine River in Dusseldorf, Germany, below an installation of wetland vegetation grown in geotextile mats made from coir. The large rock was wrapped in a polyethylene type of rope mesh and installed in the following fashion: (a) a ditch is dug; (b) the rope mesh is placed in the ditch so that enough of it is overhanging the ditch on the riverward side to wrap around the rock and have some left on the shoreward side on which to place more rock; (c) the rock is placed on the rope mesh; (d) the rope mesh is wrapped around the rock with a portion of it running up the shoreward side; and finally (e) more rock is backfilled on top of the rope mesh to hold it all firmly in place. This rock roll serves to protect the treatment from undercutting. The rope mesh contains smaller rocks and strengthens the system and is similar to the function of gabions that are discussed below. It should be mentioned that this whole system of rock rolls and geotextile mats with wetland grasses or grass-like plants, such as sedges, were placed in between large rock transverse dikes (Figure 12). The dikes were already there before this treatment was installed and to divert river currents away from the banks. The rock roll (toe protection), the transverse dikes, and the geotextile coir mats, work together to obtain wetland plant establishment and erosion control. Prior to the installation of plants,



Figure 9. Photo of bioengineering project on upper Missouri River where large rock (1.5 tons/lin ft) was used as toe protection below large coir-covered hay bales, also forming part of toe



Figure 10. Vegetation in the form of dormant willow posts (discussed later) placed landward of rock and hay bale toe

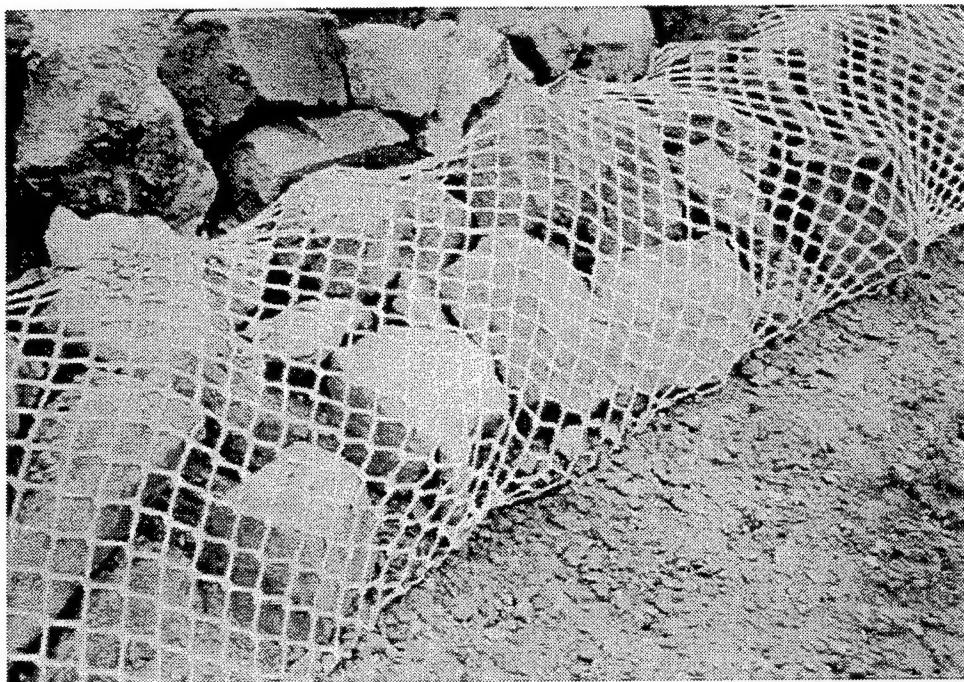


Figure 11. Rock roll used as toe protection on a bioengineering project,
Rhine River, Germany, in city of Dusseldorf



Figure 12. System of bioengineering treatments such as geotextile coir
mats with planted vegetation on them placed above a rock
roll toe and between large rock transverse dikes

even though the transverse dikes were present, an asphalt revetment used to control erosion failed because water got behind the asphalt and pushed it out. This system has been in place from 1991 to present and has withstood a large flood in 1994, the largest in the last decade, with more than a 7-m fluctuation above normal flow. The flood overtopped the treatment for several months. Because of the wetland plants' flood tolerance, the rock toe, and transverse dikes, they survived and are still controlling erosion. A key wetland plant species instrumental in the treatment's success was a sedge, *Carex hirta*.¹

Gabions are wire mesh baskets filled with rock and formed as boxes of various dimensions. The wire is either galvanized or covered with a plastic coating to increase durability. Gabions are tied together to become large, flexible, structural units and can be stacked in tiers. They can be installed in the toe zone to prevent undercutting and can be stacked or run as a revetment of gabion mattresses up into the splash and bank zones (Figure 13). They can be used in conjunction with vegetation in several ways. Often times, live, willow whips are placed in between the tiers of boxes back into soil that facilitates sprouting. When they are used as a gabion revetment and rock toe, vegetation can be placed in the splash and bank zones above them. Gabions should be used with caution in streams that have high bed-load movement with cobbles and gravels that may break the wire mesh. Also, they are susceptible to vandalism and to undercutting/overturning. If used in a stacked fashion, a geotechnical engineer should be consulted to determine stability; otherwise, overturning and sliding may be a problem.

Figure 14 is two schematics (two versions) of a hard stabilizing structure for a toe. This structure is called a LUNKERS, which is an acronym for "Little Underwater Neighborhood Keepers Encompassing Rheotactic Salmonids." The LUNKERS is designed to provide overhanging shade and protection for fish while serving to stabilize the toe of a streambank. They were first used by the Wisconsin Department of Natural Resources and described in detail by Vetrano (1988). They have since been adapted for use by the Illinois State Water Survey. They are made from treated lumber, untreated oak, or materials made from a combination of plastic and wood. They are constructed by nailing planks to the top and bottom of 15- to 20-cm spacer logs. These planks form stringers, which tie into the streambank at right angles. Planks are nailed to the top and bottom stringer boards and run parallel to the streambank. The entire structure forms a crib, which can be constructed onshore and moved by a loader or backhoe to the installation site. Once in the stream, the LUNKERS is placed in position and anchored by driving 1.5-m lengths of steel-reinforcing rod through predrilled holes in the structures and then into the streambed. These structures are set in a line that simulates the outside bend of a meander. After the structures are in place, the area behind them is filled with rock, which also is used to cover the structure, and then the entire area is covered with soil (Hunter 1991). Often, the soil is planted with various kinds of vegetation, either woody or herbaceous. Care must be taken to tie the ends into the bank with a transition of rock or into a hard point to prevent flanking.

¹ Personal Communication, May 9, 1996, Herr Lothar Bestmann, President, Ingenieurbiologie, Wedel, Germany.

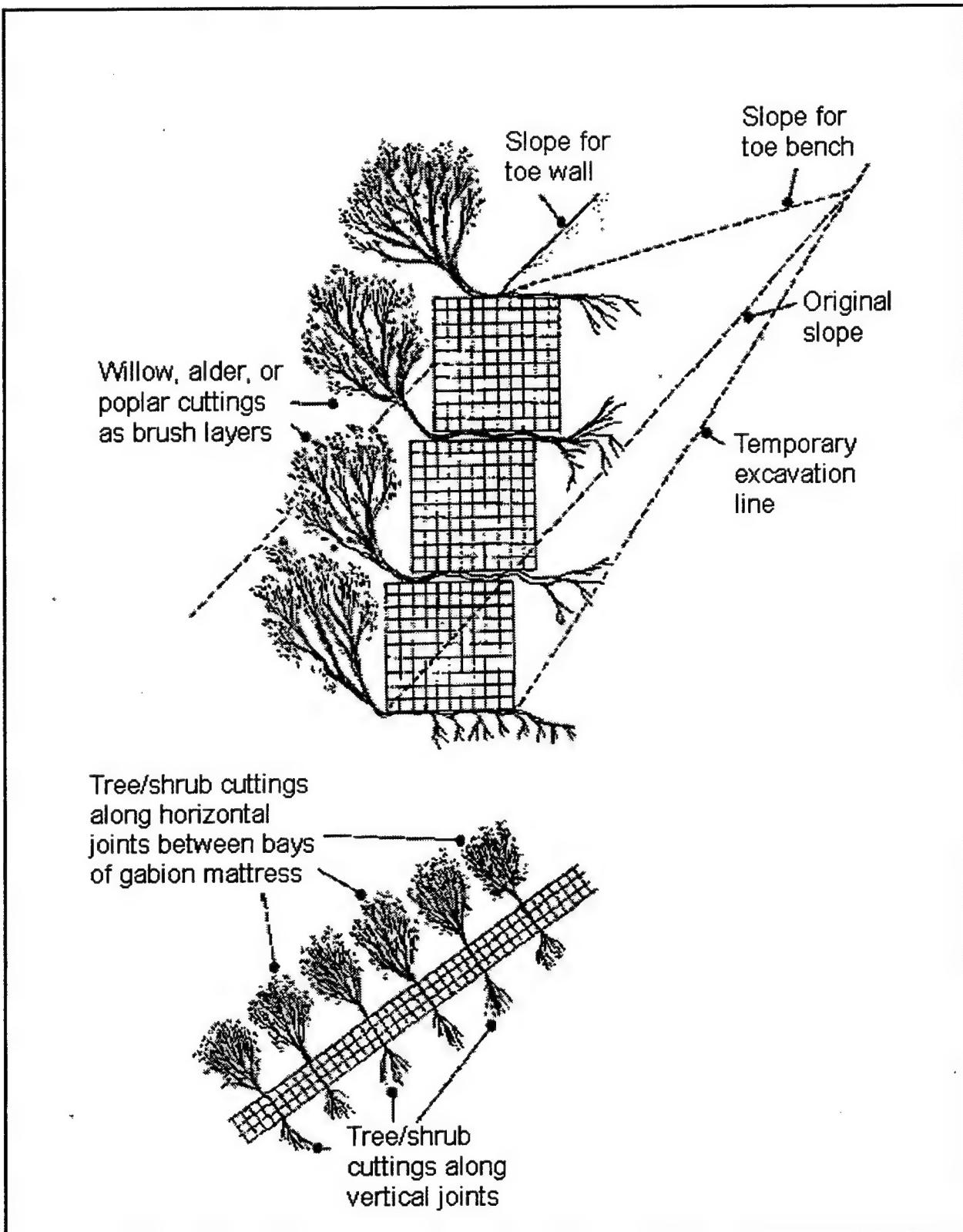


Figure 13. Schematic of gabions used with woody plants to form a hard structure to prevent undercutting and flanking (Can be used in toe zone or installed higher in splash and bank zones) (from Coppin and Richards 1990)

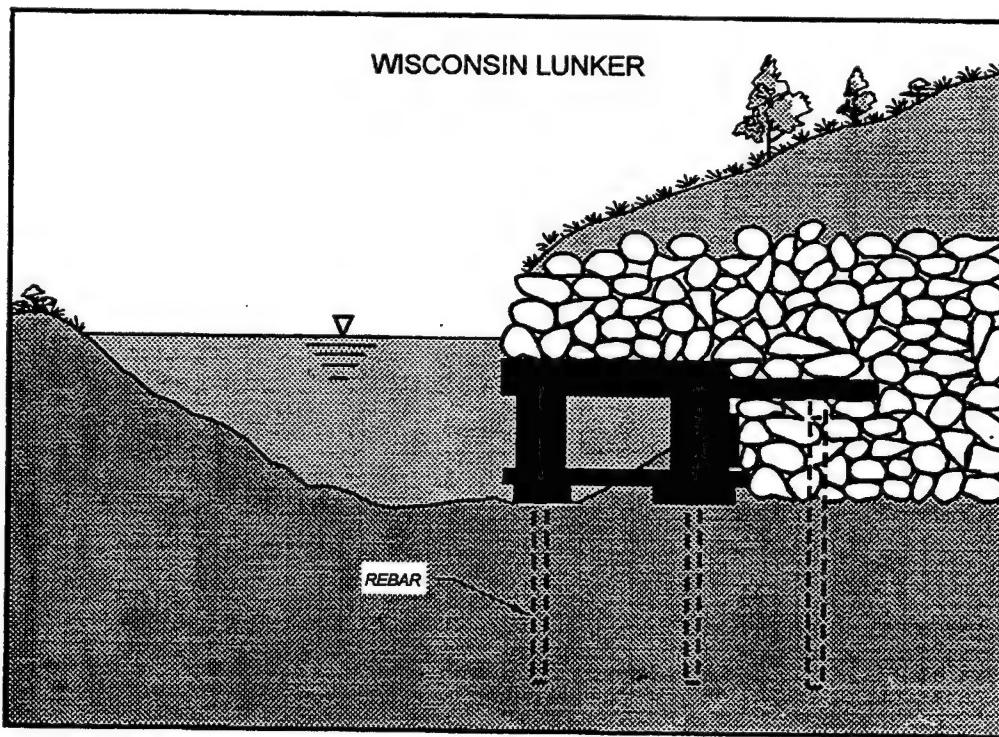
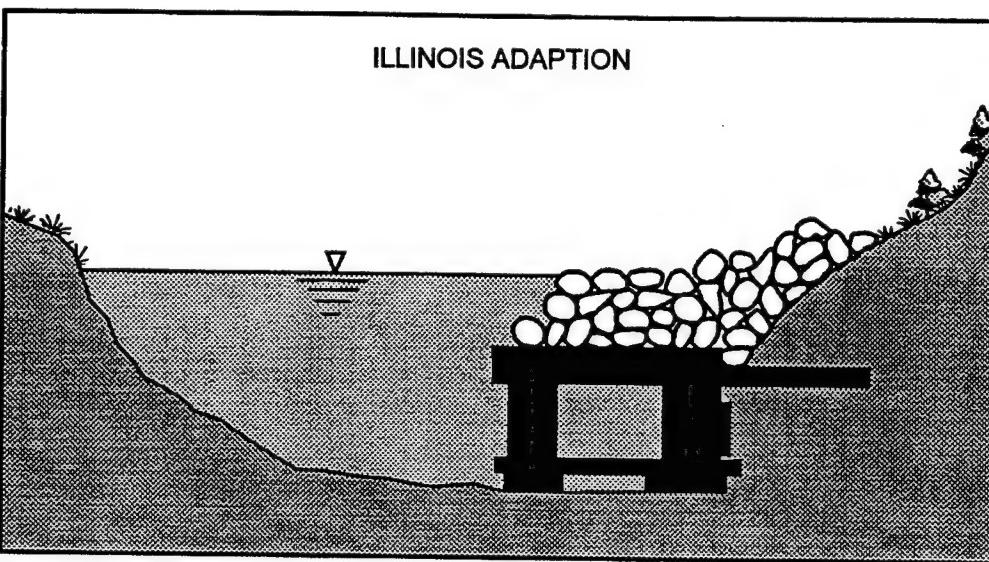


Figure 14. Two schematics (two versions) of a LUNKERS structure designed to provide overhanging shade and protection for fish while serving to stabilize toe of a streambank (Both versions use rebar although rebar is not shown on the upper schematic)

Another hard structure placed in the toe zone to stabilize the toe is a "Bank Crib with Cover Log" (Figure 15). This is described by the USDA Forest Service (1985). Like the LUNKERS, it is used to protect unstable streambanks at the toe while at the same time providing excellent overhead cover for fish. The design is a simple crib with abutment logs extending as far back into the bank as necessary to ensure structural stability (1.3 to 1.8 m in stable soils and 3 m or more in unstable soils). The lower abutment logs should be near water level and should extend 45 to 60 cm from the bank. The cover log can then be pinned to the crib log and the lower abutment. The structure can be from one to several logs high, depending upon bank height. The only materials required are logs onsite and 1.6-cm rebar to join the logs. Installing structures is fairly time-consuming, due to the amount of digging required. One crew should be able to install 6 to 9 m of crib (two crib logs high) per day if logs are reasonably close to the site. Water adjacent to some eroding banks requiring abutment work is sometimes too shallow to make effective use of cover logs. It has been noted by some that rocks need to be added below the crib log and upstream and downstream from the structure to avoid scour and flanking, respectively.

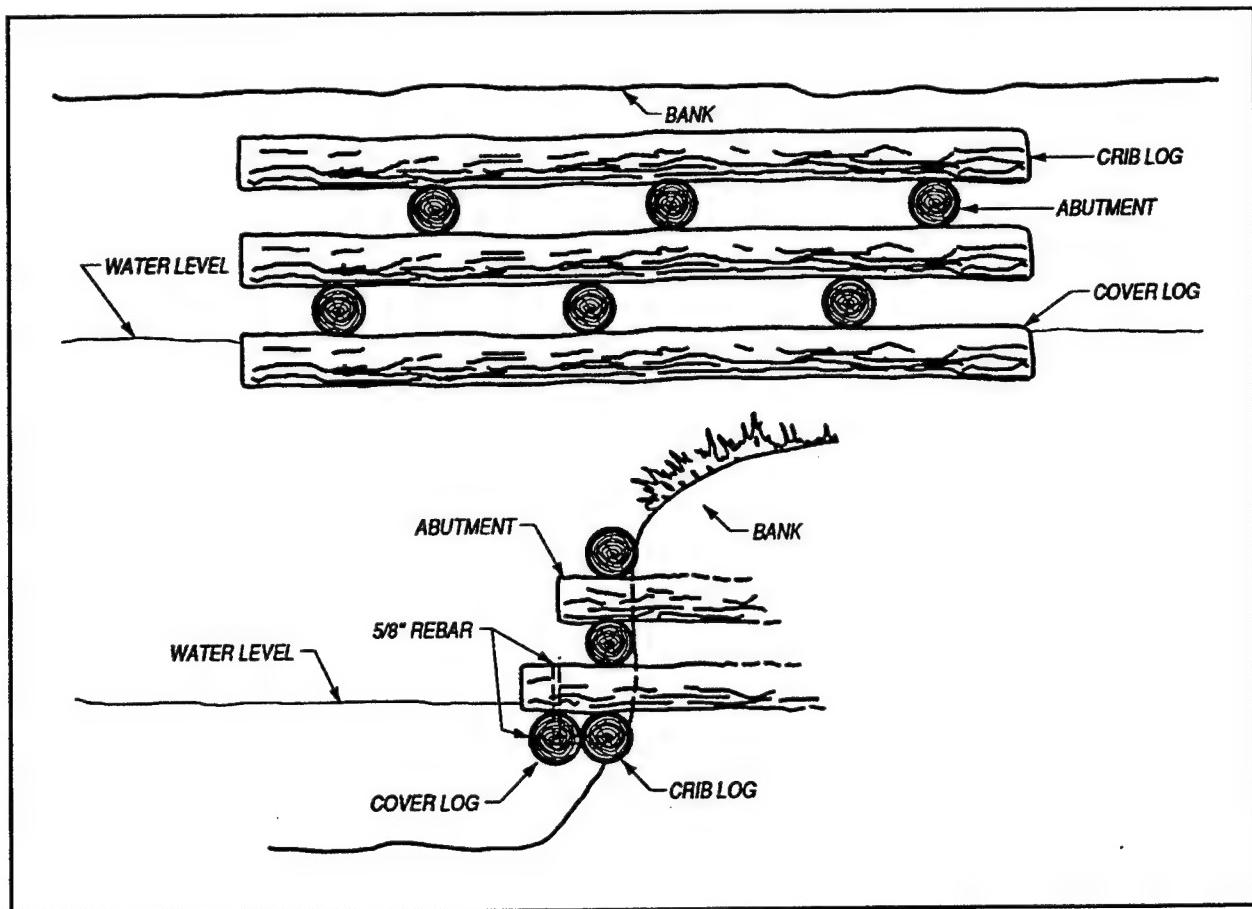


Figure 15. Bank crib with cover log used to protect unstable streambanks while concurrently providing excellent overhead cover for fish (Courtesy of U.S. Forest Service)

Log revetments are similar to bank cribs with cover logs except these are used to harden the toe and continue up the bank by lining the bank with logs (Figure 16). Then, flood-tolerant plants are placed at the top of and shoreward to the revetment. Depending on the height of the revetment, this may be in the splash, bank, or terrace zones. They are placed with butt ends facing upstream and are overlapped in a shingle fashion. They are secured with cables that are looped around the logs and then are fastened to dead men in the bank. Care must be taken to ensure their longevity by placing rock on both the upstream and downstream ends to prevent flanking of the structure. Rock should also be placed at the toe of the structure to prevent scour.

Figure 17 shows a schematic of a log revetment used on the Roaring Fork River, Colorado, near Basalt. A geotextile coir roll, called a Vegetations-Faschinen in Germany, where it originated, is placed above the top log in the revetment so its top is just even with or slightly above the normal water level. The roll is often referred to in this country under various trade names such as Fiber Roll, Fiberschine, and Bio-log. It is used in conjunction with a geotextile mat that is placed shoreward of the roll, backfilled with soil, and planted or seeded with wetland plants. The geotextile roll and mat trap sediment, allow plants to be planted in them, and are biodegradable. Note that the top log is placed in an overhanging fashion with the coir roll on top to provide shade and cover for fish. Figure 18 shows an installed log revetment on the Roaring Fork River. Report 2 presents a case study that includes evaluation of such a treatment, among others on western Colorado rivers and streams and notes local velocities to which this treatment and others were subjected. On one reach of the Roaring Fork, this structure failed because it was not keyed into the bed of the stream. Scour at the toe caused structure failure. On another reach, it worked just fine. These structures must be properly protected at the toe and at the upper and lower ends with rock and hard points, respectively.

Root wads are live or dead logs with root masses attached (Figure 19, See Bowers 1992). These are also used in the toe zone to protect it from undercutting, but must be used in combination with other materials. The fans of the root wads provide an interlocking wall protecting the streambank from erosion. The voids within and between the root wads are filled with a soil mix and planted with live, willow clumps or root pads. The

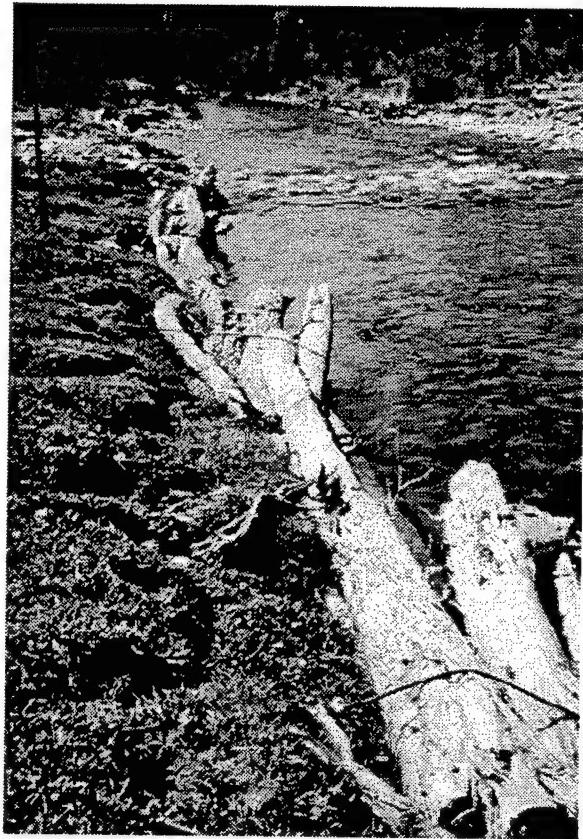


Figure 16. Log revetment, Roaring Fork River, Colorado (Note cable wrapped around logs and buried and secured to dead men in bank)

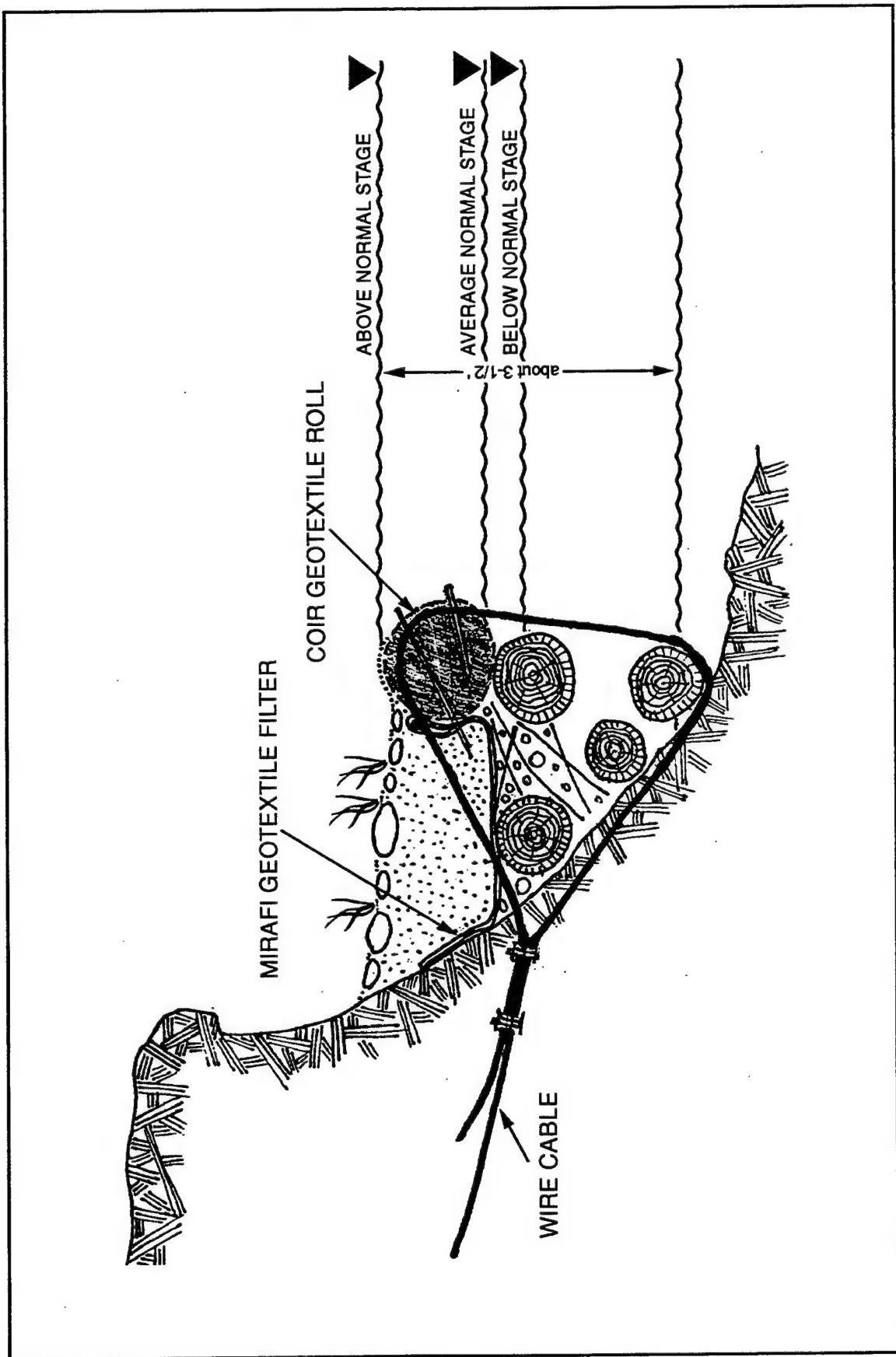


Figure 17. Schematic of log revetment with coir geotextile roll and plantings on top of backfill soil over a geotextile filter (Designed by Alan Czenkusch, Colorado Division of Wildlife)

Figure 18. Installed log revetment with coir geotextile roll combination, Roaring Fork River, Colorado (Wetland vegetation is seeded or planted in back-filled soil placed in a depression between revetment and land. Rock is placed on top to prevent scour)

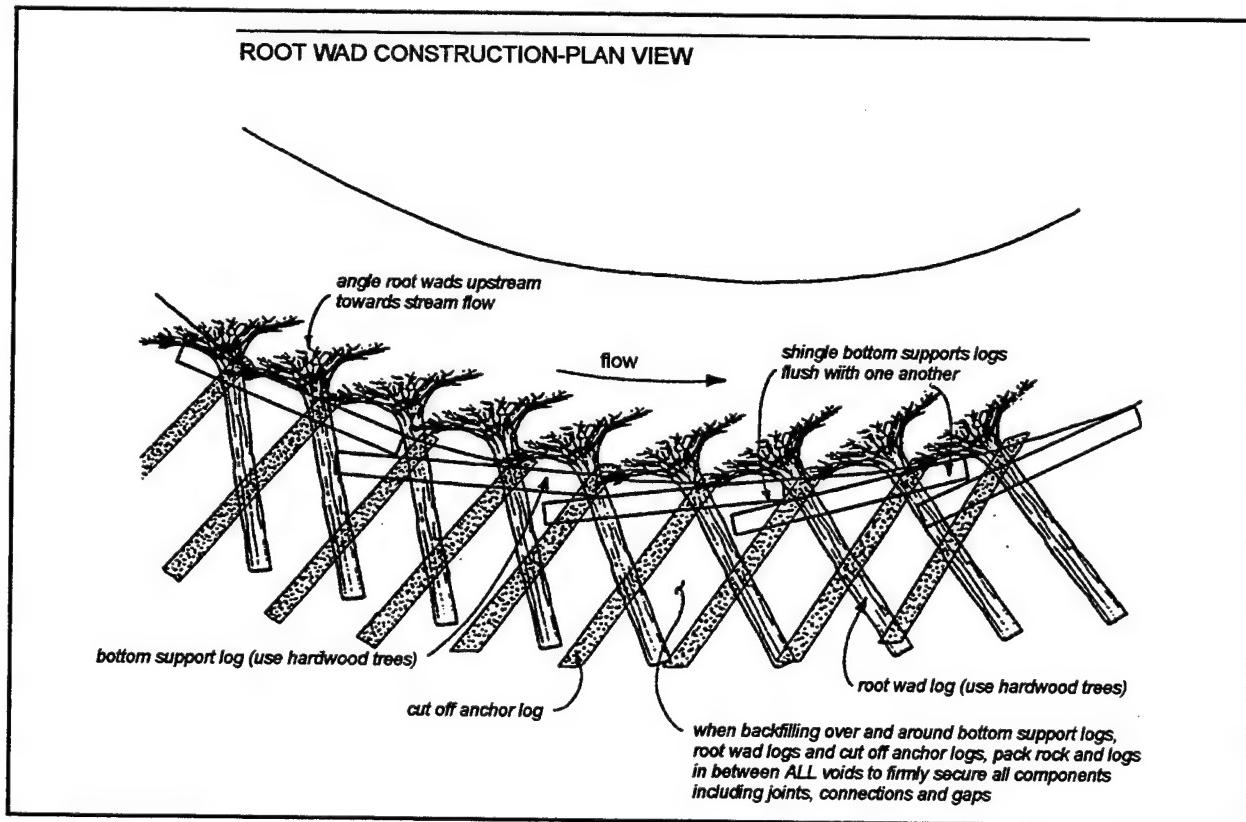
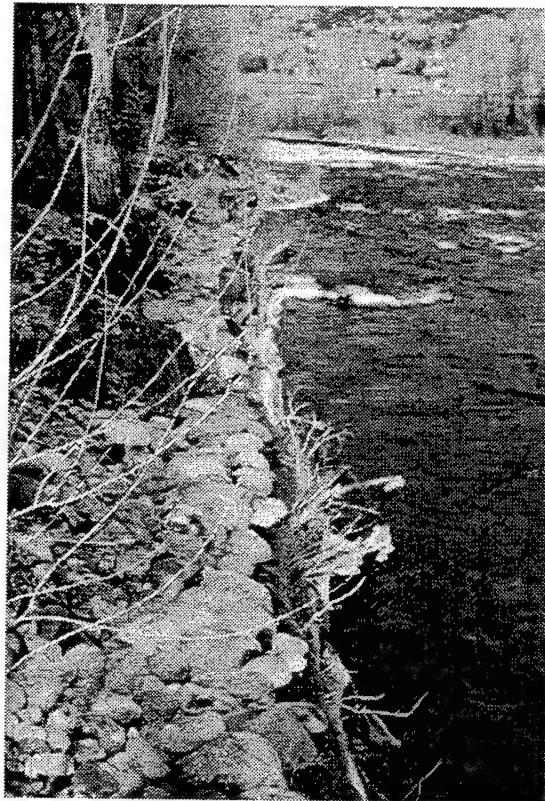


Figure 19. Schematic of root wad construction (from Bowers 1992)

root wads are laid on top of a keyed-in shelf of stone and support logs. This shelf includes a layer of bottom support logs flush with one another, shingled together, and running parallel to the streambank. The root mass should be a minimum of 5 ft in diameter and angled slightly upstream towards streamflow. This treatment should be placed at a base elevation that is consistent with water levels during the major part of the growing season, i.e., June through September. The bottom two-thirds of the root wad should be in water during that period of time. The upstream and downstream ends of the root wad treatment should be tied into hard points made from rock or some natural hard feature so as to prevent flanking.

Figure 20 shows a treatment using root wads on the Upper Truckee River in California near South Lake Tahoe, where this treatment and others were monitored for a couple of growing seasons (see also Report 2). Various local flow velocities were measured along the treatment on the fall of the hydrograph. These ranged from 1.6 to 4.0 fps at 0.6 depth of flow and 4 ft out from the right bank. The root wads sufficiently reduced local flow velocities so that vegetation had a chance to get established and stabilize the bank despite a major flood in the spring and summer of 1995 where floodwaters overtopped the bank. Rosgen¹ noted that on a root wad treatment on the Blanco River in Colorado, that local velocities in the vicinity of the root wads were 12 fps and yet willow clumps installed in with the root wads and the root wads themselves did not fail.



Figure 20. Root wads soon after installation on Upper Truckee River, California, near South Lake Tahoe (Voids within and between root wads are filled with a soil mix and planted with live, vegetative clumps or root pads, such as willow)

¹ Personal Communication, July 1996, Dave Rosgen, President, Wildland Hydrology, Pagosa Springs, CO.

Deflector dikes are any constructed protrusions into the water that deflect the current away from the eroded bank. These consist of transverse dikes, hard points, groins, bendway weirs, and stream barbs. They are usually made of rock, but other materials such as logs or trees can be used. As mentioned above in the Dusseldorf, Germany, example, bioengineered treatments often use vegetation between deflector dikes. The dikes and the bioengineered treatments work as a system to stabilize the streambank. Transverse dikes differ from hard points or groins by projecting further out into the stream. Bendway weirs and stream barbs are low rock sills. Flows passing over them is redirected so that the flow leaving the structure is perpendicular to the center line of the structure. Derrick (1996) describes the construction and use of bendway weirs both on the Mississippi River and on smaller streams in northern Mississippi. In the latter case, bendway weirs were successfully used, in part, with a dormant willow post method of stabilizing the streambank (to be discussed below). Shields, Knight, and Cooper (1995) describe the benefits to aquatic habitats on small streams in northern Mississippi by use of such weirs. The structures increased pool habitat availability, overall physical heterogeneity, riparian vegetation, shade, and woody debris density. To design deflector dikes with vegetation, persons are needed with training both in hydraulic engineering and bioengineering working as a team. Hydraulic engineers should be consulted for design, construction, and placement of the deflector dike, and bioengineers or someone with training in botany should be consulted for use and placement of the vegetation.

A combination of materials, as mentioned above, can be used in the toe zone. Deflector dikes can be used with plants incorporated in the dike system for erosion control as well as fisheries habitat. Figure 21 shows a schematic of a coir geotextile roll. As illustrated in the figure, it is used in combination with rock at the base and around the ends with some openings for the ingress and egress of fish and other aquatic organisms. The coir is stuffed into a rope mesh material made either out of coir itself or of polyethylene. The roll is planted with emergent aquatic plants. The coir accumulates sediment and biodegrades as plant roots develop and become a stabilizing system. Figure 22 shows several on a German stream. Each structure serves to redirect the current away from the bank so that vegetation can be installed in between. The plants in the structure furnish shade and cover for aquatic life. While the rock of the structure would be in the toe zone, the roll and the aquatic plants would be on top of the rock and abreast of it. The roll would actually grade into the next higher zone, the "splash zone."

Splash zone

The coir roll mentioned above can also run parallel to the bank with rock in the toe zone providing the foundation and additional protection at the base of the roll itself. Sometimes, the coir roll is all that is used in the toe zone when currents or waves are not strong or big enough to justify rock. Then, vegetation is planted or grown in the roll to form part of the splash zone. Figure 23 is a schematic of a coir roll abutted to an unshaped bank with some backfill. Figure 24a-d show such a treatment in a stream in Germany and planted with emergent aquatic vegetation, such as bulrushes,

iris, and sedges. Vegetation can be grown in the roll at a nursery and then transferred to the planting site with vegetation almost established.

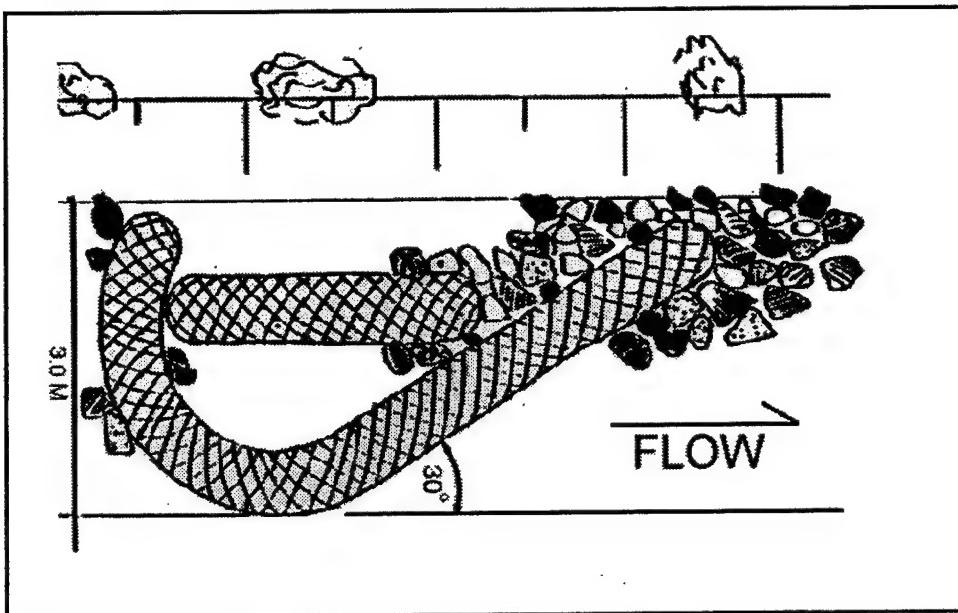


Figure 21. Schematic of a coir geotextile roll and rocks (Roll is planted with wetland vegetation. Used as a deflector system while serving as aquatic habitat) (Photo courtesy of Bestmann Ingenieurbiologie, Wedel, Germany)

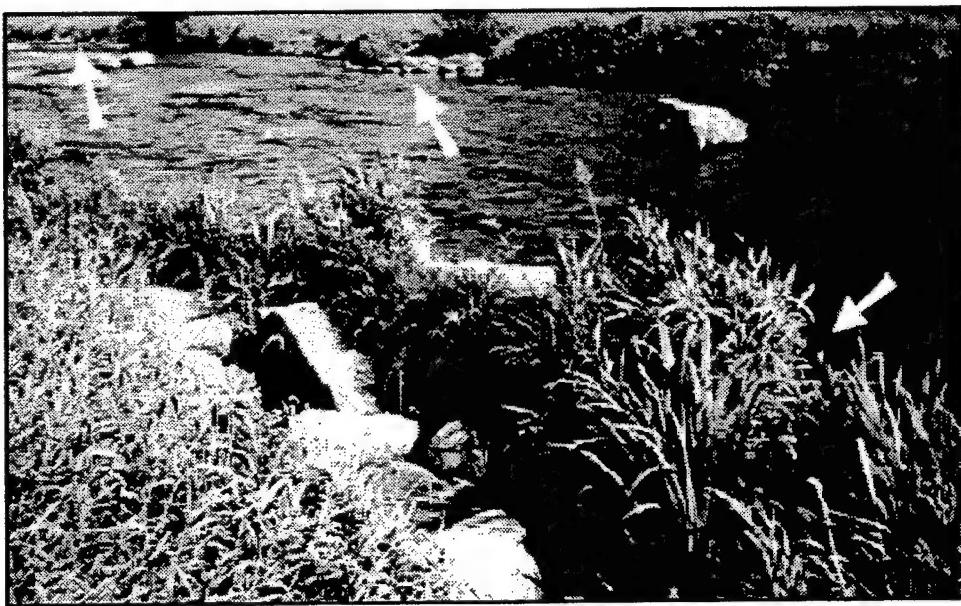


Figure 22. Photo of coir geotextile roll and rocks with wetland plants serving as a deflection system and providing aquatic habitat on a German stream (Note that two can be seen on opposite bank also) (Photo courtesy of Bestmann Ingenieurbiologie, Wedel, Germany)

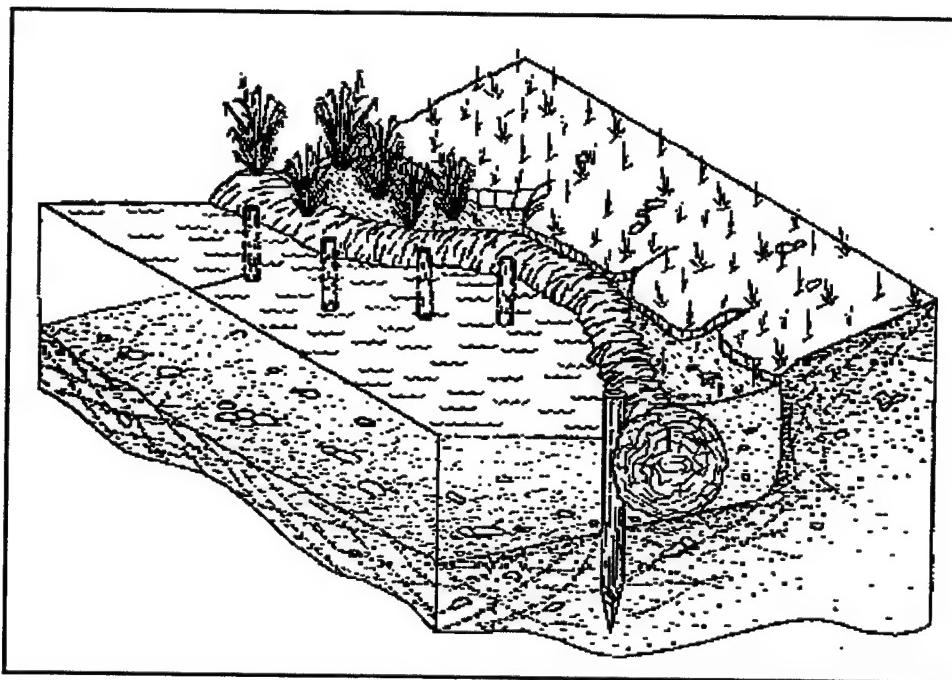
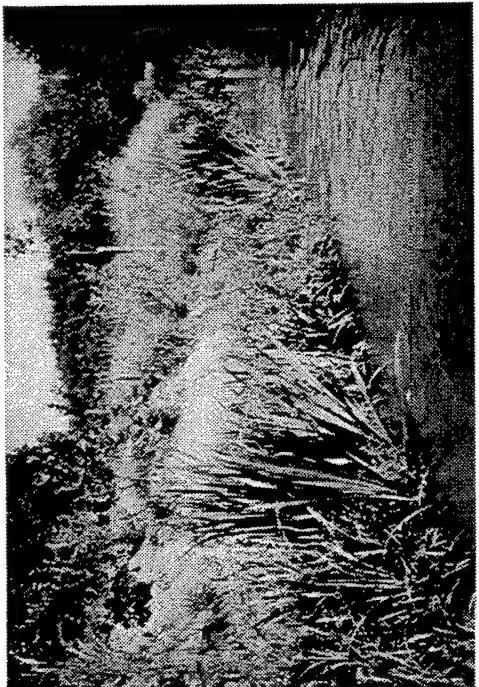


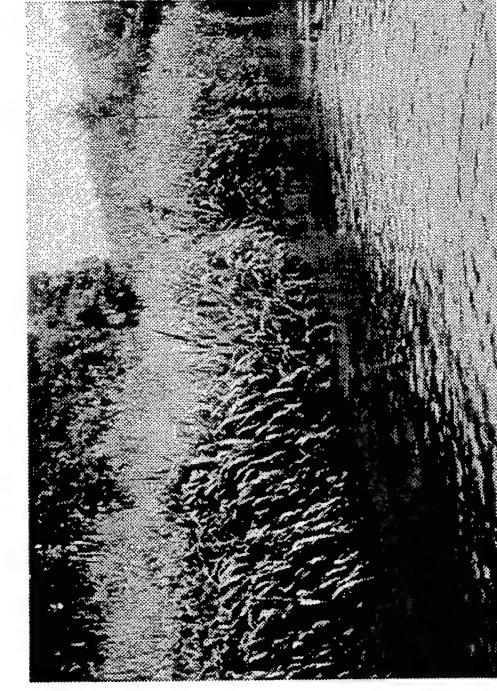
Figure 23. Coir geotextile rolls are used to stabilize streambanks and permit planting of wetland vegetation within them (Coconut fiber accumulates sediment and biodegrades as plant roots develop and become a stabilizing system) (From Bestmann Ingenieurbiologie, Wedel, Germany)

Coir rolls and emergent aquatic vegetation have also been used in this country recently. One such use was on the North River near Colrain, MA. It was monitored as a part of this work unit for two growing seasons. That case study is presented in Report 2. Both single and double coir rolls were used in different sections of the streambank. In the latter case, another roll was placed upslope from the first one. Both were planted by inserting clumps of emergent aquatic plants in them. Where overhanging banks occurred and were void of woody vegetation, an evenly sloped bank was achieved by shaping and backfilling using a small front-end loader. Shaping, however, was minimized where possible in an effort to prevent disturbance of the bank and existant vegetation. It should be reiterated that the coir rolls should be keyed well into the upper and lower ends of the reach being treated. The authors discovered after the 2-year formal monitoring period, that the coir rolls had apparently been flanked at the upper end as a result of flooding in the fall of 1995 and that the project unraveled.

The clumps of emergent aquatic plants mentioned above that were placed in the coir rolls were grown from seedlings placed in a coir wrapping and allowed to develop hydroponically (in water without soil, but with nutrients added). This leads to a well-developed, but light and easily transportable plant unit with roots readily established and poised to grow in a planting medium, such as the coir roll or in a soil substrate.



a. Coir geotextile roll being installed along a streambank in Germany



c. Coir roll a few months later



d. Closer view of coir roll a few months after plant establishment

Figure 24. Wetland plant development in a coir geotextile roll within the splash zone at a stream in Germany (Photos courtesy of Bestmann Ingenieurbiologie, Wedel, Germany)

Coir fiber mats made in various thicknesses are also used in the splash zone. These are often prevegetated at the nursery with emergent aquatic plants (Figure 25a-c) or sometimes sprigged (use of single or multiple rooted stems inserted into substrate) with emergent aquatic plants harvested from local sources. When prevegetated at the nursery, the fiber mats have the advantage of being light and can be lifted in rolls or smaller mats and transferred directly to the planting site where immediate establishment is required. They are usually tied into or keyed into whatever is used as the toe material. In the example on the North River above, 1-in.-thick mats were prevegetated and tied into the coir rolls. Coir fiber mats have the attributes of high tensile strengths, the ability to trap sediment; they are pH neutral; they facilitate root development because of the fiber network; and they are slow to biodegrade. These types of vegetated coir mats have also been used on dredged material in coastal environments with wave environments. Knutson, Allen, and Webb (1990) reported successful trials of sprigging emergent aquatic plants into such mats. This success was attributed, in part, to the attributes mentioned above, such as sediment entrapment. The blankets trapped sediment very well on the North River, which aided plant establishment initially before flanking occurred.

Single-stemmed sprigs and clumps of emergent aquatic plants and flood-tolerant grasses or grass-like plants, e.g., rushes, sedges, can be planted shoreward of hard rock toes, coir rolls, and fiber mats. They can even be used in lieu of the fiber mats if the site-specific conditions are appropriate. This may mean that the soils are more cohesive, i.e., have more clay in them, and the stream discharges at that level are not as high.

The focus in the splash zone, so far, has been on use of emergent aquatic and other herbaceous plants. Woody plants are also used in the splash zone. For these, wetland plants are used that can also withstand periods of dryness. The woody plants should be those that can sprout roots and branches from the stem. These include willow, some species of alder, dogwood, and several other species. Several possible species are listed by the Georgia Soil and Water Conservation Commission (1994) and Gray and Sotir (1996). Sometimes, woody plants may be all that are suited to the splash zone. At times, the bank geometry is very steep down to the normal flow level without a shallow water zone for emergent aquatics, or the stream system has extreme fluctuations and large silt loads that would drop sediment on emergent aquatics and bury them.

Bioengineering techniques that utilize woody plants include in part, brushmattress, brush layering, vegetative geogrids, dormant post method, dormant cuttings, and dormant root pads. All of these are usually used in combination with hard structures or materials that either deflect the current away from the bank or protect the toe and upper and lower ends. For instance, dormant root pads are used with root wads that were discussed above for the toe zone.

Brushmattress. A brushmattress, sometimes called brush matting or a brush barrier, is a combination of a thick layer (mattress) of interlaced live willow switches or branches and wattling. Both are held in place by wire and stakes. The branches in the mattress are usually about 2 to 3 years old, sometimes older, and 1.5 to 3 m long. Basal ends are usually not



a. Emergent aquatic plants in WES greenhouse nursery that were seeded on coir fiber mat



b. Emergent aquatic plants established on a coir fiber mat being rolled up in WES nursery ready for transport to bioengineering site



c. Coir geotextile mat in a roll planted with emergent aquatic plants being carried to planting site

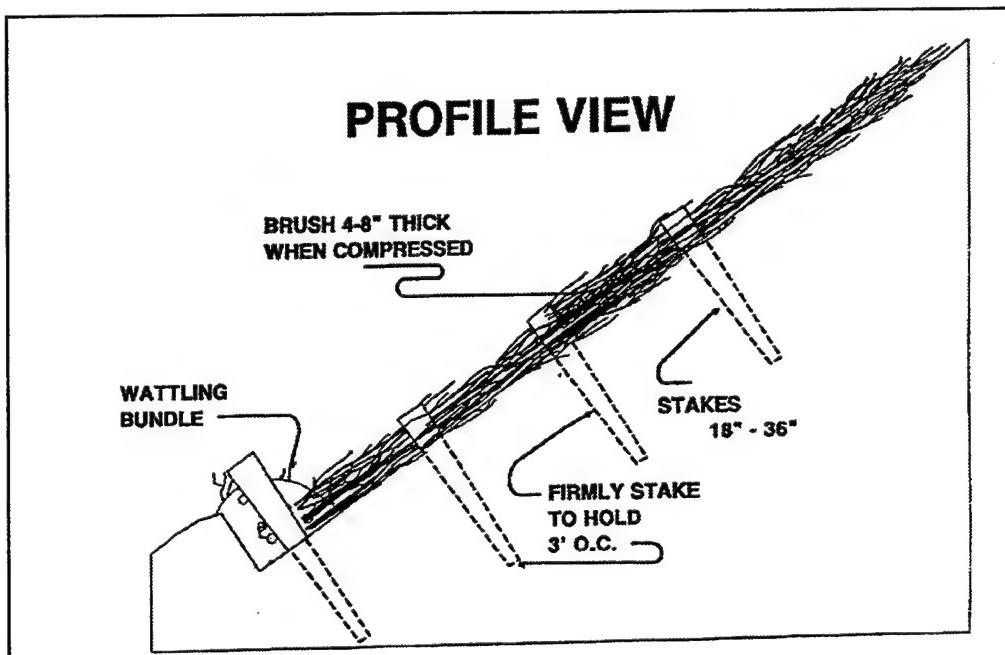
Figure 25. Coir geotextile mat being prevegetated in WES nursery in 1983 and transported to field site ready for immediate growth (Roots and stems of the plant have already been established in the mat)

more than about 3.5 cm in diameter. They are placed perpendicular to the bank with their basal ends inserted into a trench at the bottom of the slope in the splash zone, just above any toe protection, such as a rock toe. The branches are cut from live willow plants and kept moist until planting. The willow branches will sprout after planting, but care should be taken to obtain and plant them in the dormant period, either in the late fall after bud set or in the early spring before bud break. A compacted layer of branches 10 to 15 cm thick is used and is held in place by either woven wire or tie-wire. Wedge-shaped construction stakes (2 by 4 by 24 in. to 2 by 4 by 36 in., diagonal cut) are used to hold the wire in place. A gauge and type suitable for tie-wire is No. 9 or 10 galvanized annealed. It is run perpendicular to the branches and also diagonally from stake to stake and usually tied by use of a clove-hitch. If woven wire is used, it should be a strong welded wire (2- by 4-in. mesh). The wedged-shape stakes are driven firmly through the wire as it is stretched over the mattress to hold it in place. The wedge of the stake actually compresses the wire to hold the brush down. Wattle is a cigar-shaped bundle of live, shrubby material made from species that root very quickly from the stem, such as willow and some species of dogwood and alder. These bundles are laid over the basal ends of the brushmattress material that was placed in the ditch and staked. The procedure of making wattle bundles and installing them over the brushmattress material is presented in more detail below (These procedures are modified after Leiser (1994)).

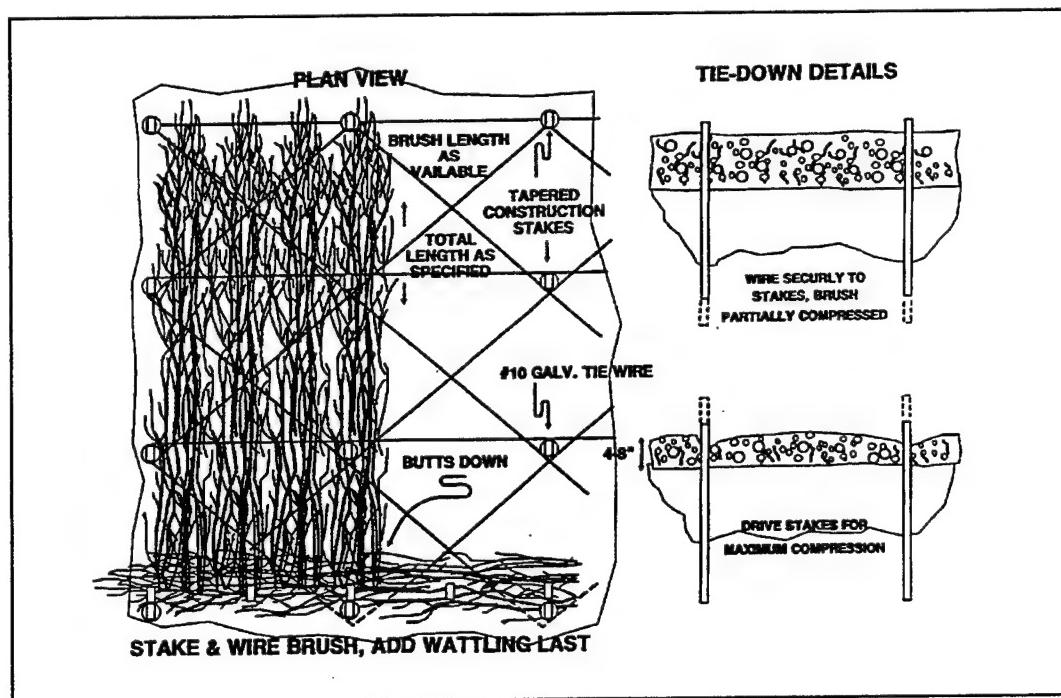
Wattle bundles may vary in length, depending on materials available. Bundles taper at the ends; this is achieved by alternately (randomly) placing each stem so that about one-half of the basal ends are at each end of the bundle. When compressed firmly and tied, each bundle is about 15 to 20 cm in diameter in the middle. Bundles should be tied with either hemp binder twine or can be fastened and compressed by wrapping "pigtailed" around the bundle. Pigtailed are commonly used to fasten rebar together. If tied with binder twine, a minimum of two wraps should be used in combination with a nonslipping knot, such as a square knot. Tying of bundles should be done on about 38-cm centers. Wattle bundles should be staked firmly in place with vertical stakes on the downhill side of the wattle not more than 90 cm on center and with the wedge of the stake pointing upslope. Also, stakes should be installed through the bundles at about the same distance, but slightly offset and turned around so their wedge points downslope. In this way, the wedged stakes, in tandem, compress the wattle very firmly. Where bundles overlap, an additional pair of stakes should be used at the midpoint of the overlap. The overlap should be staked with one pair of stakes through the ends of both bundles while on the inside of the end tie of each bundle. Figure 26a-b shows a schematic of a brushmattress and wattle. Figure 27a-c shows a sequence of installing a brushmattress with wattle at a workshop. It should be noted that because of the workshop setting at a mild time of the year, nondormant vegetative material is being used. Normally, one would preferably use dormant material.

Both brushmattress and wattle should be covered immediately with soil and tamped. Soil should be worked into both the brushmattress and wattle by both tamping and walking on it. All but the edges of the brushmattress should be covered with soil, and about 75 percent of the

wattling should be covered leaving some of each exposed to facilitate sprouting of stems rather than roots.

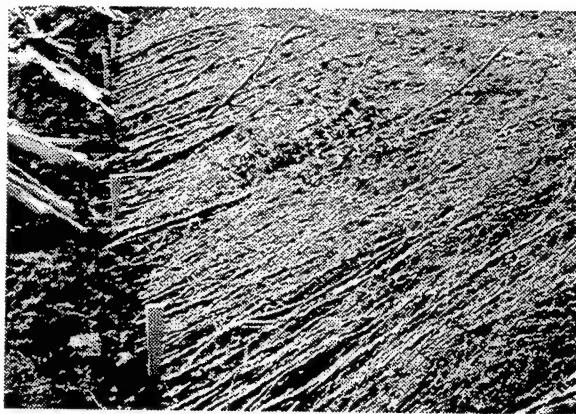


a. Profile view



b. Plan view

Figure 26. Schematics of brushmattress and wattling combination (from Leiser 1983)



a. Laying down brush (basal end first) into a previously dug trench marked by row of wedge-shaped stakes



b. Placing woven wire over willow brush



c. Stretching woven wire tight and securing by wedge-shaped stakes (Also, wattling bundles are then laid over the top of basal ends of willow in trench and secured tightly with wedge-shaped stakes)

Figure 27. Sequence of brushmattress and wattling bundle installation
(Note that this was done in dormant season in the fall even though some leaves remain on branches)

A brushmattress without sufficient rock toe protection (undersized cobble) was used on the North River, Massachusetts, and performed quite well for two growing seasons until unraveling started to occur, again because of a lack of adequate toe and upper- and lower-end protection. This was in a reach where a bankfull discharge was experienced with an associated average bankfull velocity estimated at 6.5 fps. The 350-ft radius of curvature in the project reach, as measured off a 1981 aerial photograph, results in increased localized velocities.¹ A more detailed explanation of this example appears in the case study in Report 2.

Brush layering. Brush layering, also called branch layering, or branch packing, is used in the splash zone, but only in association with a hard toe, such as rock riprap, in the toe zone. It can also be used in the bank zone as discussed later. This is a treatment where live brush that quickly sprouts, such as willow or dogwood species, are used in trenches. Trenches are dug 2-6 ft into the slope, on contour, sloping downward from the face of the bank 10 to 20 deg below horizontal (Figures 28-29). Live branches are placed in the trench with their basal ends pointed inward and no less than 6 in. or more than 18 in. of the tips extending beyond the fill face (Leiser 1994). Branches should be arranged in a criss-cross fashion. Brush layers should be at least 4 in. thick (Leiser 1994) and should be covered with soil immediately following placement and the soil compacted firmly.

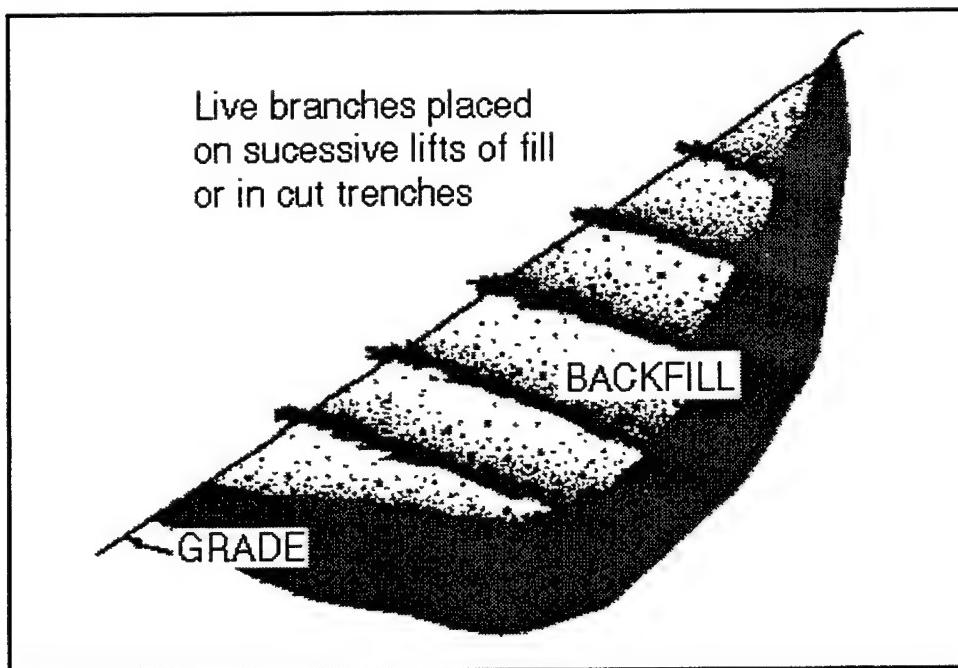


Figure 28. Schematic diagram of brush layering (from Leiser 1983)

¹ Unpublished Report, 1993, W. Goldsmith, "First year monitoring report, North River streambank stabilization bioengineering demonstration project, Colrain, Massachusetts," Contract No. DACW39-93-M-5454, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.



Figure 29. Installed section of brush layering (Note that brush has leaves because of a workshop setting. Normally, brush would be without leaves because of installation during dormant season)

Brush layering (branch packing) was used successfully on the Little Patuxent River in Maryland (Figure 30). There, it was used in combination with live fascines (wattles) and live pegs (Bowers 1992). Rock riprap was placed at the toe of the streambank for added protection. Bowers (1992) reported that the top growth of the live fascines, live branches in the branch layering, and live pegs (live stakes or cuttings) provide coverage of and protect the streambank during storm events. The species used included black willow and silky dogwood. Branch layering and live fascines were used in the low-energy zones of the river. For the areas where the thalweg came in contact with the streambank on the outside of the meander, root wads were used for protection and stabilization (Bowers 1992).

Vegetative geogrid. Vegetative geogrid is a system that can be used in the splash zone and actually extend further up the bank, into the bank, and possibly terrace zones. The system is sometimes also referred to as "fabric encapsulated soil." It consists of successive walls of several lifts of fabric reinforcement. In between the lifts are placed 5- to 10-ft-long live willow whips. This system is described by Miller (1992) and was used successfully on Acid Brook in New Jersey. It was also used on the Upper Truckee River near South Lake Tahoe along with another treatment and is discussed in more detail in Report 2. The design, according to Miller, is based on a dual fabric system modeled after synthetic fabric retaining walls used by engineers for road embankments and bridge abutments. The generic system is shown in Figure 31. Two layers of coconut fiber-based fabric provide both structural strength and resistance to piping of fine material. Piping is that process where internal erosion of soils occur; that is, water seeps in from above through a porous layer of soil, such as sand lenses, and erodes that layer from where it enters to where it



Figure 30. Brush layering with willow and dogwood branches after one growing season; installed above a rock toe (to prevent undercutting) on the Little Patuxent River, Maryland (from Bowers 1992)

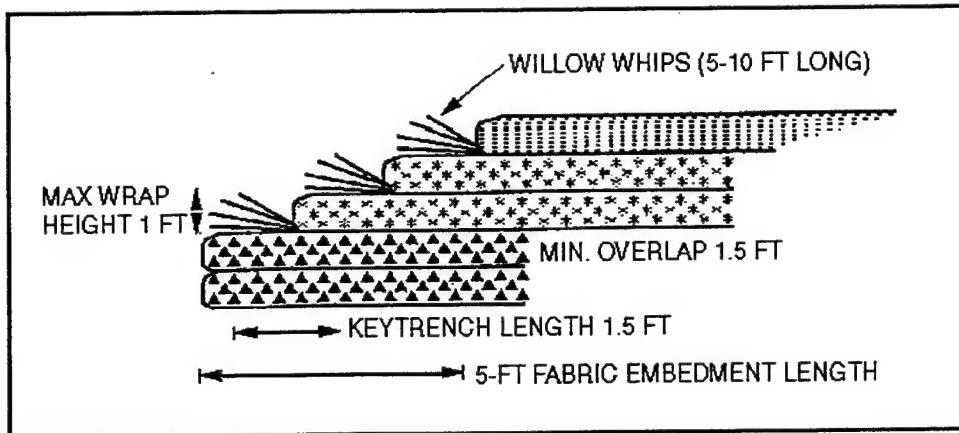


Figure 31. Cross section of vegetative geogrid, also called fabric-encapsulated soil with vegetation (adapted from Miller 1992)

exists further down slope. The inner layer is a loose coconut fiber blanket held together by synthetic mesh netting and is used to trap finds and prevent piping. The outer layer is a strong, woven coir fabric to provide structural support. Sometimes, the latter fabric is substituted by even stronger, more durable synthetic materials, that are formed by a matrix of geosynthetic bands. The disadvantage of the latter materials, however, is that they are not very biodegradable. Of course, vegetation would mask the materials so they are not visible.

Miller (1992) describes building the lifts of fabric-reinforcement as follows:

"To build the streambanks, we would first lay down a layer of each fabric in the appropriate location. We'd place fill material, compact it, and wrap the exposed fabric over the face of the fill. The fabric would be keyed back under the next layer with wooden stakes. We'd progress upwards from layer to layer, whether the slopes were vertical or at a 3:1 slope."

Figures 32 and 33 show photographs of the Upper Truckee River site both before and after construction. The latter figure was taken in July 1995 after an extended high-flow period from May 21 through July 21. There, Mr. Matt Kiese¹ described building the lifts with the use of long angle iron forms. The angle irons were 8 ft long and were fashioned to form a frame into which plywood boards were inserted. Then, the forms were wrapped with two fabrics similar to those described above and soil dumped into the forms and compacted. The fabrics were wrapped back over the soil and the forms removed. Willow whips were laid on top of each lift and then the next lift was prepared. The installation at the Upper Truckee was no more than 5 ft tall and 123 ft long. Care must be taken to provide rock or some other hard material at each upstream and downstream end to prevent flanking of the treatment. For instance, one may either tie into existing vegetation, such as trees, or create hard ends by placing rock. The latter is a safer alternative. Also, it is important to prevent scour at the bottom lift and to provide a good footing by creating a ditch and filling it with cobble or rock. The first lift is placed on top of the cobble ditch. The ditch at the Upper Truckee River site was about 2 ft wide by 2 ft deep.

During the formal two-year monitoring period, this treatment was very successful on Upper Truckee River despite the 5-year flood event in May 1995 that produced overbank flows. The treatment has remained in place since October 1993. Further discussion about this treatment can be found in Report 2.

Dormant post method. This treatment consists of placing in the splash zone and perhaps the lower part of the bank zone, dormant, but living stems of woody species that sprout stems and roots from the stem, such as willow or cottonwood. Willows are normally used and are cut into 10- to 14-ft posts when the leaves have fallen and the tree is dormant. The dormant posts store root hormones and food reserves (carbohydrates) that promote sprouting of stems and roots during the growing season. According to Roseboom (1993), dense stands of 4- to 6-year-old willows make the best harvesting areas. He also uses posts that are 4-6 in. in diameter at the base. His examples are based on fast-growing eastern species, however, and smaller willow may have to be used in the western states.

Roseboom (1993) prescribes shaping a bank to a 1:1 slope with the spoil placed in a 6-in.-deep layer along the top of the bank. In major erosion sites, post holes are formed in the bed and bank so that the end

¹ Personal Communication, October 1993, Matt Kiese, Interfluve Inc.

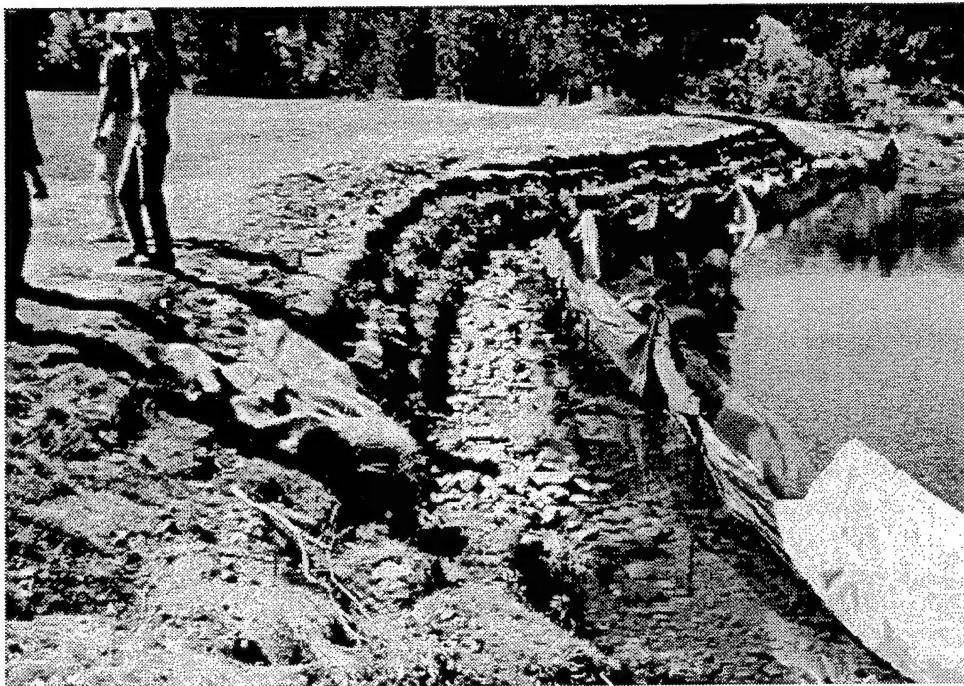


Figure 32. Vegetative geogrid during construction on Upper Truckee River, California, near South Lake Tahoe (Note rock toe that was keyed into channel bed and bank to prevent undercutting. Photo was taken in October 1993)

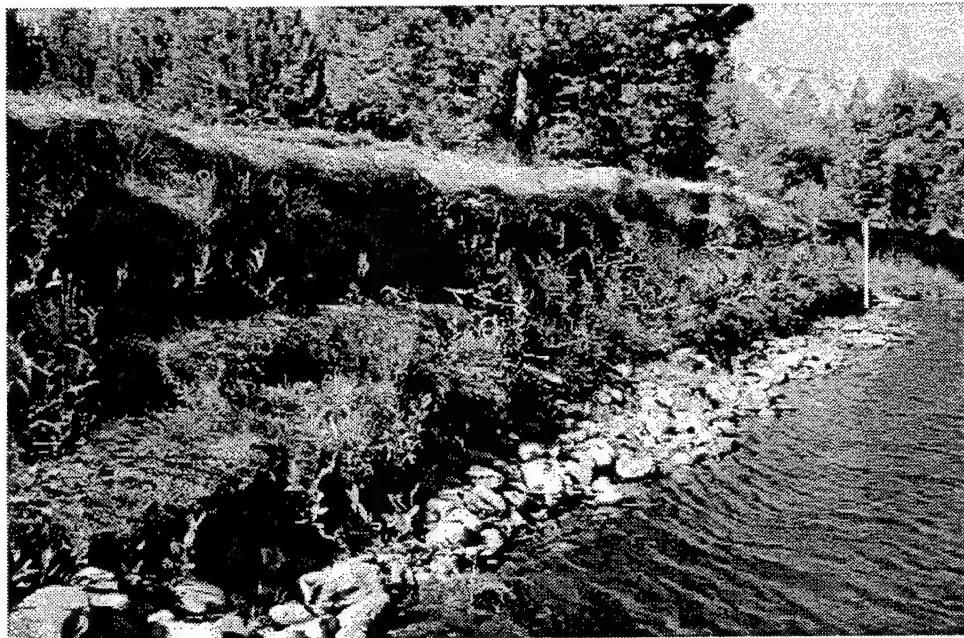


Figure 33. Vegetative geogrid in July 1995, after two growing seasons and an estimated 5-year flood during spring of 1995 (Note that live willow whips that were placed between layers of COIR fabric are sprouting and spreading) (Photo courtesy of Ms. Catherine McDonald, California State Parks)

of the post is 2 ft below maximum streambed scour (that portion of the streambed that is subject to movement). Hoag (1993) suggested that for bank stabilization, the cutting (post) should extend 2-3 ft above ground so as it leafs out, it can provide immediate bank erosion protection. He also recommended the cutting should be planted as much as 3-5 ft into the ground. If they are not this deep, moving water can erode around the cutting and rip it out of the ground. Roseboom places the posts 4 ft apart up the streambank. The posts in one row are offset from the posts in adjacent rows.

Both Roseboom (1993) and Hoag (1993) advised that willow posts should be long enough and placed deep enough to reach wet soil during dry summers. Hoag (1993) noted that plantings can occur at the water line, up the bank, and on top of bank in relatively dry soil, as long as cuttings are long enough to reach into the mid-summer water table.

An excavator that is either fitted with a long, steel ram or an auger is typically required for installation. Roseboom (1993) reported that a steel ram on an excavator boom is more efficient at depths of 6 ft in clay soils. In contrast, an auger on an excavator boom forms deeper and longer lasting holes in stoney or sandy streambeds. The ram on the excavator is for creating a pilot hole in which to place the willow post. The willow post is fitted with a cap that goes over the post, and then the heel of the bucket on the excavator is used to push the post down into the hole. Care must be taken to ensure that the post comes in contact with the soil so that no air pockets exist. In the case of the auger, this can be done by backfilling the sides of the hole in lifts and then tamping. In the case of the ram, the ram can be placed out a few inches from the post and run along the side of it into the soil so as to close the hole containing the post, especially toward the bottom of the hole.

Roseboom (1993) reported that in larger streams with noncohesive sand banks, large cedar trees cabled to the willow posts along the toe of the bank can reduce toe erosion. The cedars not only reduce bank scour while root systems are growing, but retain moisture during drought periods. Another material used for the same purpose is a coir roll mentioned earlier. In addition to trapping sediment, the coir roll can be planted with either emergent aquatic vegetation or other willow cuttings. The cedar trees and the coir roll were used in combination with willow poles on Court Creek, Illinois, along a 600-ft reach. Figures 34 and 35, respectively, illustrate work in progress and bank conditions 4 months after planting. This is described in a case study in Report 2. Velocities were measured at this site during a major 1995 flood and ranged between 1.23 to 3.11 fps. They were measured at distances immediately in front of the treatment to 3.5 ft in front and at both the surface and 0.6 ft of stream depth. It is suspected that the willow contributed substantially to reduced velocities near the bank.

Hoag (1994a) and Hoag (1994b) provided specifications for and description of another type of implement that is used to make a pilot hole for the dormant willow post. It is called "The Stinger" and has been used by the NRCS and the Bureau of Reclamation for establishing willow in riprapped revetments on shorelines of reservoirs and streambanks. According to Hoag (1994b), woody vegetation has been planted in rock riprap by

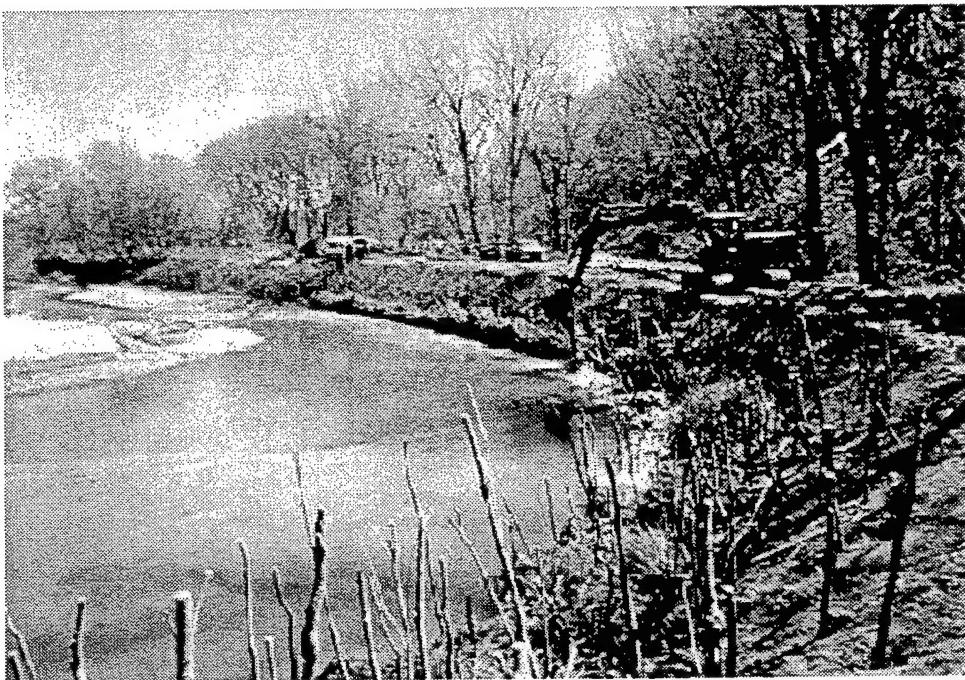


Figure 34. Dormant willow posts, coir geotextile roll, and cedar trees being installed at Court Creek, Illinois, April 1993 (Photo courtesy of Mr. Donald Roseboom, Illinois State Water Survey)

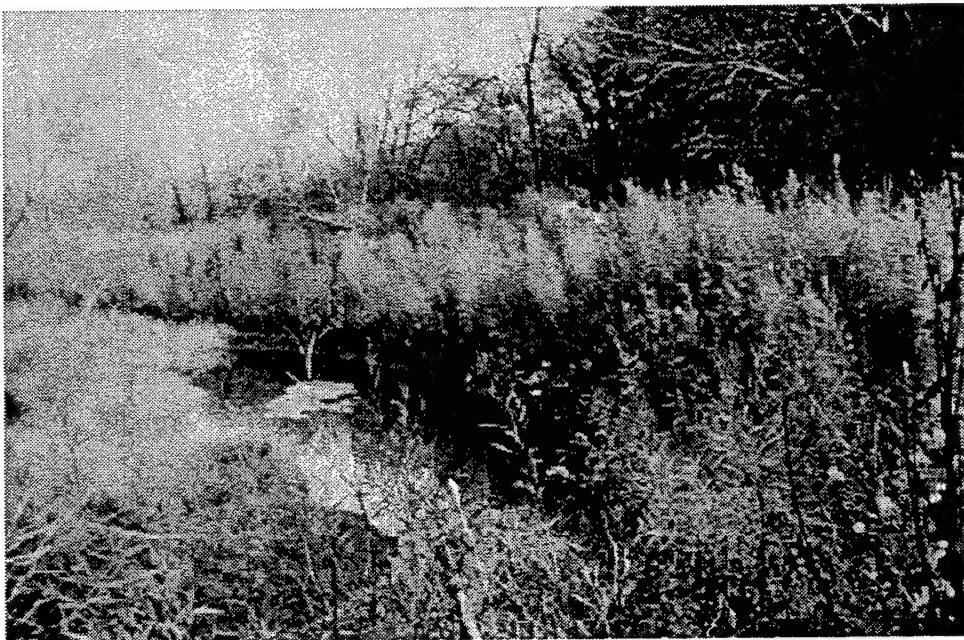


Figure 35. Court Creek site above after one growing season (Note that this is after one major flood in spring and summer, 1994, that overtopped the banks) (Photo courtesy of Mr. Donald Roseboom, Illinois State Water Survey)

dumping rock on top of them or planting through the rock riprap with a steel bar or water jet (Hoag 1994b cites Schultze and Wilcox 1985).

Hoag (1994b) states: "Neither of these methods are very efficient nor have achieved great success. 'The Stinger,' however, builds upon these methods and utilizes the power of a backhoe to plant much bigger diameter and much longer cuttings than was possible before. 'The Stinger' can plant cuttings right through rock riprap with minimal effort to better stabilize the rock, allow the cutting to be above the ice layer, and to improve the aesthetics of the riprap. 'The Stinger' can plant through 2- to 3-ft riprap, but it must penetrate the moist soil below in which to push the dormant willow pole."

"The Stinger" was used on a bioengineering project on the upper Missouri River by the Omaha District in April 1996 to place dormant willow posts between and landward of large hay bales used in the toe zone, as mentioned briefly above. "The Stinger" was used for efficiency and ease of construction (Figure 36).



Figure 36. Use of "The Stinger" to create pilot holes for dormant willow posts on upper Missouri River (CE project, Omaha District)

There are constraints in using willow posts and several questions to be addressed in the process of planning if this method is considered. These are noted by Roseboom (1993), but have been modified here:

- a. Does sunlight fall directly on the eroding bank? Willows must have at least partial sunlight to grow.
- b. Is bedrock close to the surface? The soil should be at least 4 ft deep; this can be checked with a probe.

- c. Are lenses of fine sand exposed in the eroding bank? If so, piping may be a problem, and other methods of controlling piping need to be addressed for the dormant post method to be successful. This may be done through the brushmattress technique mentioned above in combination with a geotextile filter, or it could be done by use of the vegetative geogrid technique mentioned above.
- d. Is the stream channel stable upstream of the erosion site? If the stream cuts behind the upper end of willow posts, the entire bank will erode.
- e. How deep is the stream along the eroding bank? Willow posts must penetrate to a depth that is deeper than the water near the eroding bank. There should be a shelf or at least a sloping bank that allows willow posts to penetrate at least 2 ft deeper than the deepest water at the shore, or the posts will be undercut below the root zone. If this cannot be achieved by the willow posts, then some kind of hard toe, like a rock revetment, should be used to prevent scour beneath the posts. The length of the willow posts will depend on the water depth as well as the dryness of the soil above the stream level.
- f. How wide is the stream channel at the erosion sites when compared with stable channels upstream and downstream? The channel with vegetation at the erosion site(s) should not be narrower than stable channels upstream or downstream; otherwise, vegetation could choke the channel and cause other erosion problems.
- g. Is there a source of large willows close to the site? Costs are less when willow stands are close because of less transportation costs. Also, there is less chance of mortality due to long durations of handling and possible drying of the willow.
- h. Will the site be wet during dry summers? Willow posts require considerable water while the roots are becoming established from the root primordia on the stems. For dry sites, such as in the western states of the United States, tops of willow posts should be only 1-2 ft above ground and they should penetrate into at least the capillary zone of the groundwater table. Figure 10 shows willow posts being used in eastern Montana on the upper Missouri River in combination with a line of coir-covered hay bales for toe protection. In similar cases, care should be taken to ensure the posts are cut off not more than 2 ft above ground and that they penetrate the groundwater.
- i. Can you keep cattle and other animals, domestic or wild, away from the posts during the first summer? Willows and other plants produce food for regrowth from leaf photosynthesis. If these sprouting branches with leaves continue to be browsed or if the tops of the plants continue to be cut off by beaver during the first growing season, they could die. It is best to prevent this by keeping cattle off the area and either trap beaver off the area or spray the willow stems with organic beaver deterrent sprays, made with such constituents as mountain lion urine. It should be noted, however, that beaver damage during subsequent years of development may only

promote resprouting of branches from the main stem and actually promote a shrubby-like plant. This is a positive effect from a surface roughness perspective, whereas the many branches slow the current and promote sedimentation that can lead to other plant colonization.

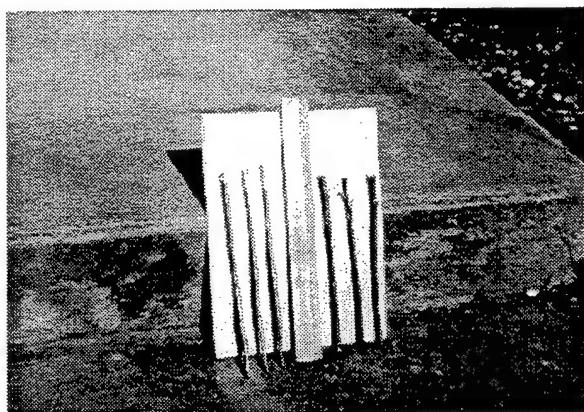
- j. Have debris jams or trees and logs forced floodwater into the eroding bank? These must be removed at least to the point where they are not directing water into a bank. Trees and logs can be moved parallel to the bank and cabled to dead men. Care should be taken, however, to ensure the upstream end is not flanked by currents, thus possibly jeopardizing that bank reach.

The dormant post method using willow provides a low-cost bank stabilization method with both wildlife and fisheries benefits. Roseboom (1993) reported that the method has received widespread support by both the agricultural and environmental communities: Farm Bureau, Soil and Water Conservation Districts, American Fisheries Society, and The Nature Conservancy. The willows hold the soil together long enough for other plants to become established on the bank through succession. Together, they provide a natural system of food and cover. More can be found on this method in the case study provided in Report 2.

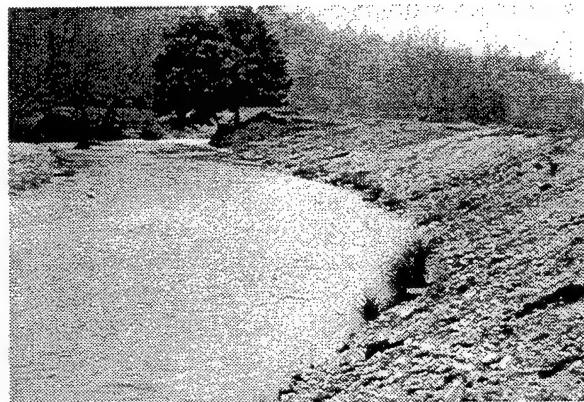
Dormant cuttings. Dormant cuttings, sometimes called “live stakes,” involve the insertion and tamping of live, rootable cuttings into the ground or sometimes geotextile substrate. In higher velocity streams, such as over 5 fps, this method usually is applied in the splash zone with a combination of other methods, such as the brushmattress and root wad methods. Dormant cuttings can be used as live stakes in the brushmattress and wattling as opposed to or in combination with the wedge-shaped construction stakes previously mentioned. They can also be placed adjacent to the brushmattress. They can also be used in the matrix openings of the root wad logs along with root pads of other vegetative materials. If cuttings are used alone in the splash zone, the toe should be very stable and velocities should be less than 5 fps. Also, the soil in which they are placed should be fairly cohesive. Figure 37a-c shows an application of bankers (*Salix X cocceti*) and streamco (*S. purpurea ‘streamco’*) willow cuttings that were installed on Irish Creek in North Carolina by the NRCS. These willow were installed on a fairly cohesive bank on a straight reach with a stable toe.

Dormant cuttings can vary in size, but are usually a minimum of 0.5 in. in diameter at the basal end (Hoag 1994b). Cuttings can be used that are up to 2 to 3 in. in diameter and have been noted by Hoag (1993) to have the highest survival rates. Cutting length is largely determined by the depth to the mid-summer water table and erosive force of the stream at the planting site (Hoag 1993). Plantings can occur at the water line as in the splash zone, up the bank into the bank zone, and on top of the bank (terrace zone) in relatively dry soil, as long as cuttings are long enough to reach into the mid-summer water table (Hoag 1993).

Cuttings should have their side branches cleanly removed and the bark intact so that the cutting is one single stem. Care should be taken to make clean cuts at the top and the bottom so that the bark is not separated from



a. Eight-inch live cuttings of Streamco and bankers willow used to stabilize Irish Creek



b. Photo of Irish Creek during first growing season



c. Reach of Irish Creek stabilized with cuttings of willow
(Photo taken four growing seasons after planting)

Figure 37. Irish Creek, North Carolina, stabilized with cuttings of bankers and streamco willow (Photos courtesy of USDA Natural Resources Conservation Service)

the underlying woody tissue. Also, one should be sure they are cut so that a terminal bud scar is within 1 to 4 in. of the top because cuttings put out their greatest concentration of shoots and their strongest ones just below an annual ring (formed from a terminal bud scar). At least two buds and/or bud scars should be above the ground after planting (Gray and Leiser 1982). Tops are normally cut off square so they can be tamped or pushed easily into the substrate. The basal ends are often angled for easy insertion into the soil. When selecting material from a natural stand, care should be taken to see that the harvest material is free from insect damage, disease, and splitting.

Root pads. Root pads are clumps of shrubbery composed of such species as willow (shrubby forms), redosier dogwood, European alder (*Alnus glutinosa*), and others. They are often used in the splash zone as a part of root wads where the root pads are positioned in between them. Root pads can also be used further up the slope into the bank and terrace zones. Caution should be exercised in planting these during the dormant season. They can be removed from harvest areas and placed at the project site with front-end loaders. "Veimeer" type spades are sometimes used on root pads where species have deep penetrating roots, whereas front-end loaders are used on species whose roots spread out more at the surface. Placement of root pads on slopes greater than 1V:6H should include securing the root pads by driving 2-in.-diam, 18- to 24-in.-long wooden stakes through the pads at 2- to 3-ft intervals (Logan et al. 1979).

Bank zone

The bank zone may be exposed to considerable flooding and current and wave action. If only mild current and wave action is expected, sodding of flood-tolerant grasses like reed canary grass, buffalo grass (*Buchloe dactyloides*), or switchgrass (*Panicum virgatum*) can be employed to provide rapid bank stabilization. Usually, the sod must be held in place with some kind of wire mesh, geotextile mesh such as a coir fabric, or stakes. A soilless system for growing wetland plants in coconut fiber mats (coir mats) was discussed above for the splash zone and can be extended up into this zone as well.

Instead of using sod in this zone, the California Department of Parks used seed from wetland plants, such as various sedges and grasses, in combination with burlap and a coir woven fabric (0.8 lb/sq yd) laid over the seed (Figure 38). This whole system was placed in the bank zone above root wads and willow clumps that were installed in the toe and splash zones, respectively. The combination of root wads, willow clumps, and this seeding and burlap/coir combination was stable in most reaches where it was installed although vegetative cover from the planted seed was less than expected. This treatment, along with others, is described in Report 2.

To augment the sodding practice for this milder energy regime, shrub-like willow, dogwood, and alder transplants or 1-year-old rooted cuttings are effectively used in this zone (Edminster, Atkinson, and McIntyre 1949; Edminster 1949; Seibert 1968). These transplants or cuttings should be planted about 0.5 m apart and in rows. Further planting practices can be

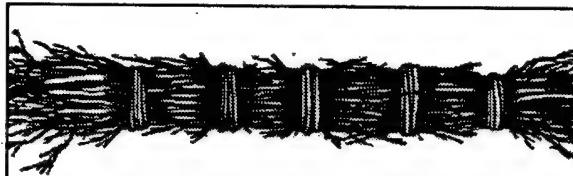


Figure 38. Burlap and coir woven fabric laid over sedge and grass seed, Upper Truckee River, California (Note that fabrics were keyed in at top and bottom in trenches and securely staked with wedge-shaped stakes) (Photo courtesy of Interfluve, Inc.)

found in Edminster, Atkinson, and McIntyre (1949) and Edminster (1949). Newly planted banks are usually subject to additional erosion, and the shrub plantings should have mulch placed over them to serve as temporary protection. Mulch of woody plant branches are best for this and should be the heaviest on outside curves of the stream where the current strikes the bank. The mulch should be tied down with chicken wire or wire laced between stakes since the mulch may float away when flooded (Edminster 1949).

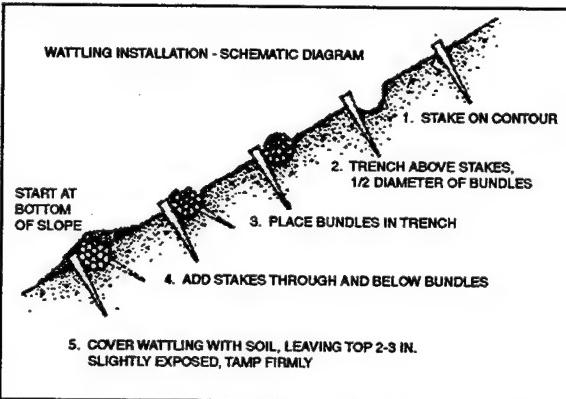
Where severe erosion is expected and currents on the bank are expected to exceed 8 fps, methods such as the brushmattress discussed for the splash zone above should be carried up into the bank zone. Additionally, two other methods using woody materials are appropriate for this zone. They include contour wattling and brush layering.

Contour wattling. Contour wattling was discussed above as an integral component of the brushmattress. In the bank zone, and in this context, it may be used independent of the brushmattress along contours. Sometimes, the term "fascine" will be seen in lieu of the term wattling. The bundles are buried across the slope, parallel or nearly parallel to the stream course, and supported on the downhill side by stakes (Figure 39a-c). They also have stakes driven through the them and can be either living or constructed from wood as previously described. The sprouting attributes of the brush species used, such as willow, combined with the supportive attributes of the structure itself provide an integrated system of stems, roots, wire, and stakes that hold the soil in place. When used on slopes, they protect against erosion caused by downward water flow, wind action, trampling



PREPARE WATTLING: CIGAR-SHAPED BUNDLES
OF LIVE BRUSH WITH BUTTS ALTERNATING
8-10 IN. DIAM, TIED 12-15 IN. O.C. SPECIES
WHICH ROOT ARE PREFERRED.

- a. Schematic of wattling bundle with preparation specifications (from Leiser 1983)



- b. Procedures for installing wattling bundles on slope in bank zone (from Leiser 1983)



- c. Wattling (fascine) bundle being installed in the bank zone
(Note that wattling should not be covered completely
with soil; leave top 2-3 in. exposed for sprouting pur-
poses (Photo courtesy of Ms. Robin Sotir, Robin Sotir
and Associates)

Figure 39. Wattling bundle preparation and installation

caused by wildlife and livestock, and the forces of gravity. Further descriptions of wattling (fascine) construction can be found in Edminster (1949), Schiechtal (1980), Gray and Leiser (1982), Allen and Klimas (1986), Coppin and Richards (1990), Georgia Soil and Water Conservation (1994), and Gray and Sotir (1996).

Contour wattles (fascines) are often installed in combination with a coir fiber blanket over seed and a straw mulch. In this way, slopes between the wattles may be held firmly in place without development of rills or gullies. Figure 40 illustrates this and was prepared by Robin B. Sotir and Associates for the U.S. Army Engineer District, Nashville, and successfully used on the Tennessee River near Knoxville, TN. It should be noted that there was significant toe protection in the toe zone with rock riprap; however, there was also overbank flooding shortly after installation of the contour wattles, and the treatment was stable.

Brush layering. Brush layering can be used in the bank zone as it was in the splash zone except with some modifications. Geotextile fabrics, such as coir woven fabrics, should be used between the layers and keyed into each branch layer trench, so that unraveling of the bank does not occur between the layers (Figure 41). Before the geotextile fabric is applied, the areas between the branch layers should be seeded with flood-tolerant grasses or grass-like plants, like sedges, and then covered with a straw mulch. This method was used to stabilize levees in low-lying areas of fen districts in England (from Gray and Leiser (1982) who cited Doran (1948)). Slope heights, the vertical distance between the layers, should not exceed 3 times the length of the longest brush in the trench. This would be similar in principle to a sloping reinforced earth revetment (from Gray and Leiser (1982) who cited Bartos (1979)) where metal strips are placed essentially horizontally in successive layers up the face of a slope. In a reinforced earth revetment, it is common practice to make the strip length (or width of reinforced volume) about one-third the slope height (Gray and Leiser 1982).

Brush layering lends itself to partial mechanization because the benches can be excavated with a small backhoe or grader. Regular construction equipment, such as a front-end loader with a grapple on the bucket, can be used for hauling and placing the brush. Backhoes or similar equipment can also backfill.

The choice between wattling and brush layering, according to Gray and Leiser (1982), should be based on economics, the potential stability of the fill (in this case, stability of the streambank), and the availability of suitable plant materials. Generally speaking, brush layering is considered to be less expensive than contour wattling. Brush layering stabilizes a fill or bank to greater depths, but more plant material is required than for contour wattling. However, if the streambank is disturbed to the extent that rebuilding and reshaping is necessary, brush layering may be the better alternative, because of its ability to stabilize a bank to greater depths.

Again, as it was in the earlier parts of this report, emphasis should be placed on prevention of flanking of the bioengineering treatment. In this case, either contour wattling or brush layering treatments should be protected with some kind of hard structure both upstream and downstream of

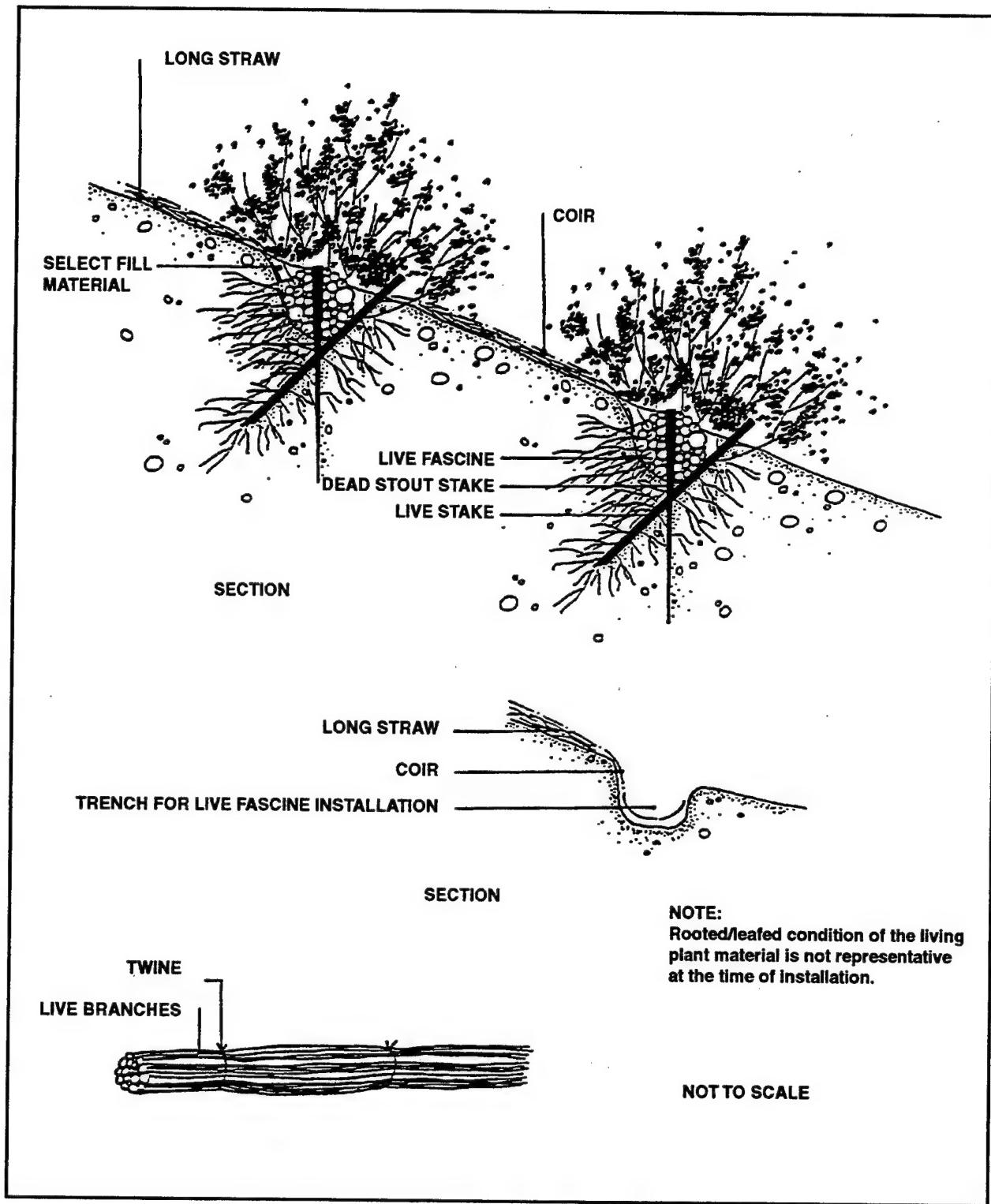


Figure 40. Schematic illustration of live fascine bundles with coir rope mesh fabric and long straw installed between bundles (from U.S. Army Corps of Engineers 1993; schematic drawn by Robin B. Sotir and Associates, 1993)

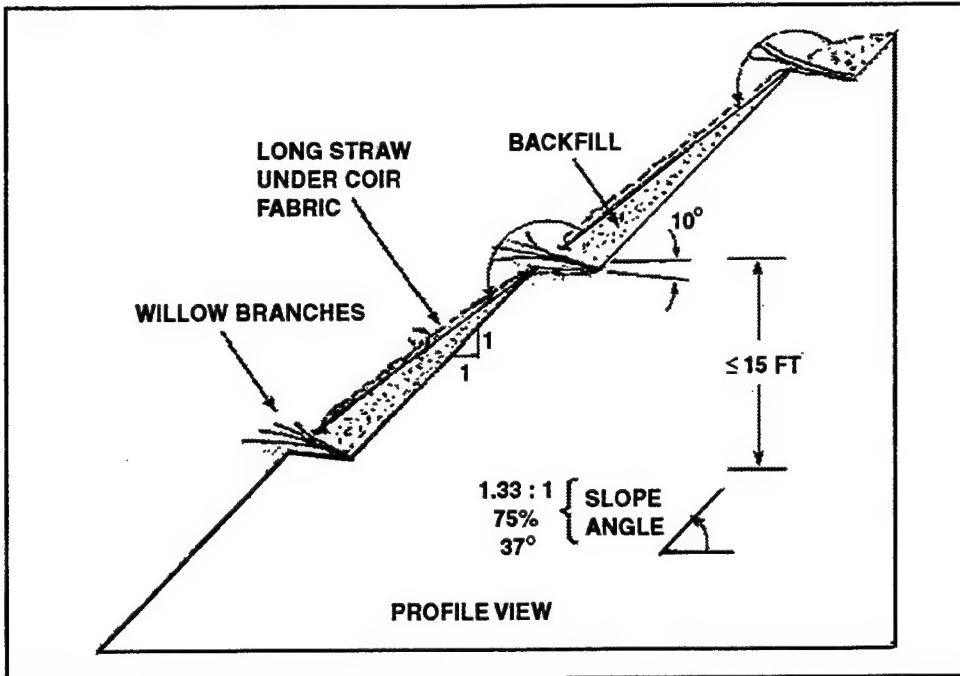


Figure 41. Brush layering with coir woven fabric and long straw under fabric (Coir fabric and straw help control rilling and gullying between layers) (adapted from Gray and Leiser 1982)

the treatment. If natural hard points, such as large boulders, rock outcroppings, or hard geological strata, are not present, then one should consider use of a rock refusal. This would be rock riprap that starts at the bottom of the bank, continues up the bank, and is keyed into the bank (Figure 4).

Terrace zone

The terrace zone, as mentioned earlier, is rarely flooded and usually not subjected to erosive action of the stream except during occasional flooding. When flooded, it receives overbank flooding with return flows that can cause gullying and rilling to occur on the fall of the hydrograph. It is in this zone that vegetation is needed with deeply penetrating roots to hold the bank together, such as larger flood-tolerant trees. Grasses, other herbs, and shrubs can be planted in between the trees, depending on their shade tolerance. Bioengineering, per se, is not normally used in this zone unless there are deep gullies that have occurred as a result of return flows or slopes still occur in this zone that are 3H:1V or greater. In these cases, branch layering or contour wattling treatments are often employed across the gully or on the contours of the slope.

Care should be taken in using large trees in this zone. They should be planted far enough back from the bank that their shade does not kill out the vegetation in the splash and bank zones. Narrow channels, especially, can be completely shaded from one side. When trees are planted in this zone, they are planted either as container-grown (potted) or bare-root plants. Suggestions vary on the size of container-grown plants. Leiser

(1994) suggests using containers with a minimum size of 9 cu in. with a depth of 8 in. and a maximum size of no larger than a 1-qt milk carton. Plants in larger containers increase the cost for purchase and planting substantially. Survival is frequently reduced because of limited root systems in relation to size of the tops of the plants (Leiser 1994). The important thing to remember is to have a container with growing medium well filled with roots so that the roots and medium form a cohesive unit when removed from the container.

Woody materials (Hoag 1994b), whether they be grown in containers or derived from cuttings, should be used only in the bank and terrace zones when the following conditions exist:

- a. Where long periods of inundation or water erosion are minimized.
- b. Where adequate moisture is available, i.e., natural precipitation is adequate for species selected or plants are irrigated.
- c. Where there is no competing vegetation or a 30-in.-diam area around plant is scalped of competing vegetation at planting time.
- d. Where plants have a low risk of physically being pulled or eroded out due to a shallow rooting system during the first year after being planted.

Hydroseeding and hydromulching can be a useful and effective means of direct seeding in the terrace zone, particularly on slopes greater than 3H:1V and places where it is difficult to get equipment. Sometimes, it is possible to work from a small barge and use hydroseeding and hydro-mulching equipment on the barge (Figure 42) and blow them onto the bank. If seeds are blown on in a water slurry, a generic type mix is suggested by Leiser (1994):

Grass seed	50 lb/acre
Woodfiber mulch	500 lb/acre
Water	As needed
Fertilizer (if not broadcast)	250 lb/acre

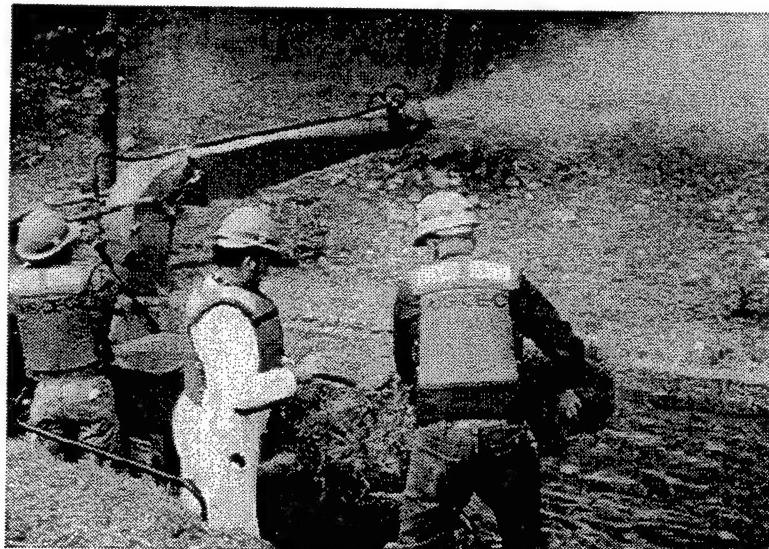


Figure 42. Hydroseeding and mulching operation from a barge

According to Leiser (1994), the slurry should be continuously mixed as ingredients are added and mixed at least 5 min following the addition of the last ingredients before application begins. The slurry should be continuously mixed until used, and application must be completed within 2 hr of the last addition. Water should be potable or at least filtered so as not to clog spraying equipment. The slurry should be applied at a rate that is nonerosive and minimizes runoff.

On level areas and slopes of less than 3H:1V, seed should be broadcast by mechanical hand or power-operated spreaders or drilled on contour with a Brillion or range drill as site conditions permit. Broadcasted seed should be covered by raking or dragging with a chain, chainlink fence, or other approved means unless previously planted with cuttings or transplants (Leiser 1994).

Sometimes surface drainage water intercepts the terrace zone from inland areas and can cause gullying not only in the terrace zone, but in the other zones on the bank. This water should be diverted or controlled with a small furrow or trench at the top of the bank. This trench should be sodded to prevent erosion.

Velocities for Design Purposes

The purpose of this section is to provide some velocity information that bioengineering systems have been noted to sustain so that planners and designers have a basis for choosing bioengineering systems and the particular kind of system. Some of the velocity information was derived from the literature while other information was measured at local points at case study locations where bioengineering treatments were installed. Velocities vary so much within a stream that local velocities near the treated section are the most valuable. Admittedly, the measured velocities are much lower than considered maximum threshold values that could be sustained by the installed structures. This is because when measurements were made, they were made with current meters in the local vicinity of the bioengineering treatment on the fall of the hydrograph when water levels and currents during flood events were not a safety hazard. Remote current meters exist, but would have been silted in or damaged by debris flow during these flood events.

Most of the velocity information in the literature concerns itself with turf grass cover that was designed for erosion control ditches or waterways. Little information exists on combinations of systems, i.e., bioengineering treatments, containing both herbaceous and woody species. Engineer Manual (EM) 1110-2-1205 (U.S. Army Corps of Engineers 1989) states that herbaceous or woody vegetation may be used to protect channel side slope areas (depending on the frequency of inundation, velocity, and geotechnical constraints to infrequent flooding) and other bank areas where velocities are not expected to exceed 6 to 8 fps. Information concerning influence of vegetation (bermuda grass) or variation of velocity with depth below water surface is shown in Henderson and Shields (1984) who cites Parsons (1963).

The splash and bank zones will be the principal focus for bioengineering applications. It is in these zones that the designer must tailor vegetation types and bioengineering structures to be commensurate with velocities that they can sustain. Hoag (1993) suggests that maximum flow velocities should not exceed 3 fps for herbaceous plantings, 3-5 fps for woody and herbaceous mixed plantings, 5-8 fps for woody plantings alone, and that maximum flows above 8 fps require soil-bioengineering approaches.

For the case studies examined and monitored for this report, measured velocities for local flow conditions around the bioengineering treatment never exceeded 10 fps. Maximum velocities sustained and recorded by bioengineering treatment types are shown in Table 2. As previously mentioned, these may not represent the maximum velocities encountered, as they were usually taken on the fall of the hydrograph. Also, local roughness imparted by the bioengineering treatment would have slowed velocities in its vicinity.

Table 2
Local Flow Velocities Sustained by and Recorded for Various Bioengineering Treatments Monitored by This Project

Location	Type of Bioengineering Treatment	Maximum Velocity Recorded, fps	Notes
Roaring Fork River, CO	Log revetment with coir geotextile roll and grass seeding above roll (See Figures 17 and 18)	10.0	Logs anchored in the bank with heavy duty cables. Rock jetties used for hard points at strategic points.
Snowmass Creek, CO	Root wads with large root pads (clumps) of willow (See Figures 19 and 20)	8.7	Lack of maintenance during spring 1994 (additional root wads at scour points) caused partial washout of the upper meander during spring flood of 1995.
Upper Truckee River, CA	Root wads with large clumps of willow (Figures 19 and 20)	4.0	Lower velocities measured in and around bioengineering treatment than further out into channel; this can be attributed to larger roughness coefficient.
Court Creek, IL	Dormant willow posts with rock toe (Figures 34 and 35)	3.1	Four rows of willow posts on 4-ft centers; 10- to 15-ft-long cedar trees between 1st two rows of willow; coir geotextile roll and riprap placed at toe along meander apex.

Notes: These are local flow velocities noted in this table and were measured by a flowmeter; all treatments were in their second growing season after major flood events when these measurements were taken.

Table 2 shows maximum local flow velocities around a root wad structure with willow root pads to be 4.0 and 8.7 fps for two different treatments at two geographic locations, Upper Truckee River, California, and Snowmass Creek, Colorado. It is suspected that these kind of structures, if properly installed, could sustain velocities much higher than these. It

was noted earlier in this report that D. Rosgen¹ measured local flow velocities around root wads on the Blanco River, Colorado, to be 12.0 fps.

Some of the treatments noted in Table 2 had some partial failures even though at least half of the reaches where these were installed remained intact and the treatments continued to function. The treatment containing the log revetment with coir geotextile roll on the Roaring Fork River, Colorado, experienced some failure. The lower half of the reach in which it was installed washed out after a major flood in the spring of 1995. This was due to the problem of insufficiently burying and keying in the bottom-most log of the revetment into the streambed. Consequently, scour undermined the structure, and it failed along the lower half of the reach.

The root wad structure on Snowmass Creek, Colorado, had a partial failure. After the spring runoff in 1994, the sponsor noticed minor damage around certain critical points that needed maintenance, the addition of more root wad logs. The contractor instead placed rock at inappropriate places. Consequently, the creek flooded during the spring runoff of 1995, and the outside of the lower section of the upper meander washed out and eroded about 6 ft of bank. In these two cases, it points to the need for properly keying in structures for toe and end protection and to monitoring and possible maintenance early in the life of a bioengineering project. Early monitoring and maintenance can actually prevent these failures and other more severe impacts caused by the failures. For example, if the root wads in the Snowmass Creek example above were dislocated, they could cause more severe erosion than normal erosion without the bank treatment. This early monitoring and maintenance should be included in the construction contract at the outset.

¹ Personal Communication, July 1996, Dave Rosgen, President, Wildland Hydrology, Pagosa Springs, CO.

3 Plant Acquisition, Handling, and Timing of Planting

Almost all of the plants used in bioengineering can be considered wetland plants, either obligative or facultative. Some of the exceptions would occur in the terrace zone that is infrequently flooded; however, all must be somewhat flood tolerant. Both herbaceous and woody plants are used. Herbaceous plants may be emergent aquatic plants like rushes and sedges or grasses and other forbs that require nonaquatic but moist conditions at least part of the year. The herbaceous plants are usually acquired as vegetative material such as sprigs, rhizomes, and tubers. Sometimes seed is acquired, but is used when the threat of flooding is low in the bank and terrace zones. Otherwise, they would wash out quite easily unless they are seeded underneath or in a geotextile mat or fabric that is securely anchored.

Woody plants used for bioengineering purposes usually consist of stem cuttings, those that quickly sprout roots and stems from the parent stem. These are plants such as willow, some dogwood, and some alder. They can be supplemented by bare-root or containerized stock, particularly in the bank or terrace zones where they are not subjected to frequent flooding. Gray and Sotir (1996) list several such plants that can be used in bioengineering and relate their flood tolerances, along with some other characteristics.

There are three suitable methods to acquire plants for bioengineering treatments. Each has, according to Pierce (1994), noteworthy advantages, but critical disadvantages that make plant acquisition and handling an important and complex process. The three methods are to: (a) purchase plants, (b) collect plants from the wild; and (c) propagate and grow plants.

Regardless of the method chosen, it is necessary to conduct the following steps (Pierce 1994):

- a. The available hydrologic regime and soil types should be determined. General positioning of the plant type, e.g., emergent aquatic, shrubby willow, should be in accordance with the plant zone (splash, bank, and terrace) defined in Chapter 2.
- b. A list of common wetland plant species in the region and more preferably in the watershed containing the stream of concern

should be prepared, and these should be matched to the hydrology and substrate of the target streambank reach to be addressed.

- c. Species should be selected that will match the energy of the environment and the hydraulic conveyance constraints that may be imposed by the situation. For instance, one must be careful to use low-lying and flexible vegetation that lays down with water flows if hydraulic conveyance must be maximized. In such cases, use flood-tolerant grasses or grass-like plants and shrubby woody species.
- d. Species should be selected that will not be dug out or severely grazed by animals, especially muskrat (*Ondatia zibethicus*), nutria (*Myocastor coypus*), beaver, Canada geese, and carp (*Cyprinus carpio*). Other animals may influence plant growth and survival. If plants chosen are unavoidably vulnerable to animal damage, then plant protection measures must be used, such as fencing, wire, or nylon cages around them or use of repellents.
- e. Additional special requirements and constraints of the site should be determined. For instance, some sites may be prone to sediment deposition or have a bank geometry that is almost vertical. In such cases, it may be difficult to obtain success with emergent aquatic plants that may become covered with sediment and suffocate or which have water too deep in which to grow unless the bank is reshaped. The former situation may necessitate the use of willow that can be planted as cuttings or posts and be less susceptible to complete coverage by sediment.
- f. A suite of species that would be suitable should be prepared. This may be limited to those currently available from commercial sources if there is no possibility to collect in the wild or have plants contract grown.

Pierce (1994) also gives a number of steps and advantages and disadvantages of the three methods of acquiring plants, and these have been adapted with some modifications below. Each project will have unique situations, but the following will serve as a guide.

Purchasing Plants

The steps for purchasing plants are as follows:

- a. A list of wetland plant suppliers should be acquired, such as "Directory of Plant Vendors," (USDA Soil Conservation Service 1992). Vendors' catalogs and plant availability lists should be requested.
- b. The condition in which the plants from each supplier are to be delivered should be determined—potted, bare root, rhizomes and tubers, or seed. This is important because if the plants are to be used in the splash zone where they may be partially covered with water, seed of emergent aquatic plants will not germinate underwater.

- c. The plant list should be matched against species availability, and one should not assume that all species advertised will be available in needed quantities.
- d. Samples should be ordered, if available, and plant condition and identification verified.
- e. A flexible delivery schedule should be negotiated allowing for unpredicted delays in planting.
- f. Some suppliers may grow plants on contract, but it will be necessary to contact them several months to a year before the plants are needed.

Advantages

The advantages of purchasing plants are as follows:

- a. Plants are readily available at the planting location in predicted quantities and at the required time.
- b. No special expertise is required to collect or grow the plants.
- c. No wild source for the plants must be found, and there are no harvesting permits to obtain from State or local governments.
- d. Cost can be more readily predicted and controllable than harvesting from the wild or growing one's own.

Disadvantages

The disadvantages of purchasing plants are as follows:

- a. Plants may arrive in poor condition.
- b. Selection of species is limited.
- c. Plants may not be adapted to the local environment. Contract growing may solve this problem.
- d. Cost may be high and shipping cost needs to be considered.
- e. Quantities may be limited.
- f. It may be necessary to store large quantities of plants and consequently necessitate procurement of adequate and appropriate storage facilities.

Collecting Plants From the Wild

Collecting plants from the wild may be very demanding because of hard-to-reach plants that are off main access routes. Wild plants must then be moved immediately to a nursery or holdover site or to the project site. Logistical and plant handling problems need to be carefully assessed and solutions planned well ahead of time. Care should be taken if this method is selected because of the possibility of contaminating the harvested donor plants with unwanted weedy species that could become a problem at the project site. Samples should be collected ahead of time in order to determine what kind of problems will be encountered in collecting, transporting, and storing each species. Caution should be exercised in collecting plants from harvesting areas so that the plant community is not extirpated, left functional, and the ecosystem not damaged. This can be done by not harvesting in one spot, but dispersing the harvest areas. Care should be taken by harvesting only fairly common plants. Certainly, rare plants should be avoided.

Advantages

The advantages of collecting plants from the wild are as follows:

- a. Plants are likely to be ecotypically adapted to the local environment.
- b. Plants can often be collected at a low cost.
- c. Plants can be collected as needed and will not require extended storage.
- d. Availability of species is very flexible and can be adjusted as the need arises.
- e. No special expertise is required to grow the plants.
- f. A very wide diversity of plants is available.

Disadvantages

The disadvantages of collecting plants from the wild are as follows:

- a. Weedy species may contaminate the source area and be inadvertently transplanted.
- b. A suitable area must be found, and more than one donor area may need to be located.
- c. Plants may not be in an appropriate condition for planting. For instance, they may be highly stressed, diseased, or insect infested.
- d. Species must be accurately identified, or rare plants or weeds may be harvested by mistake.

- e. Cost of collection and logistics may be very high.
- f. Outdoor hazards such as snakes, adverse weather, noxious plants, e.g., poison ivy and stinging nettles, parasites, and other inhibiting items may interfere with collection efforts.
- g. It is often necessary to procure a permit for collecting from native plant sources and wetlands, in particular.

Growing Plants

Plants to be grown for planting can be grown in a greenhouse or other enclosed facility or, in the case of emergent aquatics, outdoor ponds or troughs containing water. In either case, the plants must first be acquired from the wild or other growers and propagated. If seeds are used for propagation, they must first be stratified (subjected to various treatments such as soaking and temperature differences), but germination requirements for most wetland plant seeds are unknown. If a greenhouse is to be used, a number of limitations and constraints must be overcome, such as room for pots, adequate ventilation, and requirements or problems associated with fertilizing, watering, and disease and pest control.

Plants can be grown in coir carpets (Figure 25a-c), mats, or rolls, to facilitate early establishment, ease of transport, and rapid development. Emergent aquatic plants, especially, may be hydroponically grown in the greenhouse or in outside troughs. Then, they can be transported to the planting site ready to grow with roots already established in the carpet, mat, or roll. The U.S. Army Engineer Waterways Experiment Station (WES) used a coir carpet for this purpose in 1983 for growing and transporting ready-to-grow plants to a site in Mobile Bay for erosion control of dredged material. This same concept can be used along streambanks and can be used to an advantage when one is in an area with short growing seasons or where rapid installation is mandatory.

Advantages

The advantages of growing plants are as follows:

- a. All of the advantages of purchasing plants can be realized.
- b. The variety of species available can be as diverse as for plants collected in the wild, and plants can be planted in large quantities.
- c. Plants can be available earlier in the season than purchased or collected plants.
- d. Low cost is one of the primary reasons to grow stock for planting.

Disadvantages

The disadvantages of growing plants are as follows:

- a. Space and facilities must be dedicated to growing plants.
- b. Personnel with time and expertise to grow the plants may not be available.
- c. There is an up-front investment in both fixed and variable overhead items in order to establish a growing facility, and it may not be justified unless there is a large and continuing need for planting stock.

Handling of Plant Materials

Plants need to be handled carefully to ensure their survival between the phases of acquisition (purchasing, growing, or harvesting from the wild) and transplanting because they will undergo transportation and planting shock. Many problems associated with poor plant survival occur from the handling of the plants between the nursery or collection site and the project planting site. Generally, the plant material needs to be kept cool, moist, and shaded (Hoag 1994b). They must be treated as living material; if the living attributes are lost, then the project is much more prone to fail even though dead plant materials in a bioengineering treatment can offer some erosion control through their physical attributes, e.g., acting as bank armor, runoff retention through checkdam effects, current and wave deflectors. Plants are most easily collected when dormant. When plants are dormant, there is substantially more forgiveness in how they are handled.

Woody plants

Woody plants, particularly cuttings, should be collected when dormant; their survival decreases a lot if they are harvested and planted in a nondormant state. With bareroot or unrooted cuttings, keep them cool, moist, and in the dark until they are ready to be planted (Hoag 1994b). They can be stored in a large cooler at 24-32 °F until just before planting. Cuttings can be stored in this manner for several months (Platts et al. 1987). The cuttings can be kept in a cooler, root cellar, garage, shop floor, or any place that is dark, moist, and cool at all times (Hoag 1994b). Often, cuttings are placed on burlap and covered with sawdust or peat moss and then covered with burlap after being moistened.

Hoag (1994b) advocates soaking of cuttings for a minimum of 24 hr, whether they are coming out of storage or directly after harvesting in the late winter to early spring (Hoag, Young, and Gibbs 1991a,b; Hoag 1992). Some research recommends soaking the cuttings for as much as 10-14 days (Briggs and Munda 1992; Fenchel, Oaks, and Swenson 1988). The main criterion is that the cuttings need to be removed from the water prior to root emergence from the bark. This normally takes 7 to 9 days (Peterson and

Phipps 1976). Soaking is important because it initiates the root growth process within the inner layer of bark in willows and poplars (Hoag 1994b).

When woody plants are moved from the nursery, holding, or harvesting area, to the project site, they should continue to receive careful handling by keeping them moist and free from wind dessication. The latter can be achieved by ensuring they are covered with a light-colored (to reflect heat) and moist tarp. In the case of cuttings, they can be moved to the project site by moving them in barrels with water in them or some similar method. Actual planting of the plants shall follow the digging of holes as soon as possible, preferably no longer than 2-3 min, so that the excavated soil does not dry out. Use only the moist, excavated soil for backfill of the planting hole. Backfill should be tamped firmly to eliminate all voids and to obtain close contact between the root systems and the native soils. When using containerized or balled and burlap stock, excess soil should be smoothed and firmed around the plants leaving a slight depression to collect rainfall. Plants should be placed 1 to 2 in. lower than they were grown in the nursery to provide a soil cover over the root system (Leiser 1994).

Herbaceous plants

Plant handling requirements of herbaceous plants are even more rigorous than woody plants as a general rule because they are usually obtained in the spring when nurseries have them ready to ship or when they are readily identified in the wild for collection. At those times, they are very susceptible to dessication mortality. Consequently, they must be kept in a moist, shaded condition, or even better, in water-filled containers from the time of collection from the wild or receipt from the nursery to the time of transplanting. If herbaceous plants are identified and tagged for collection in the spring or summer, they can be collected when dormant in the late fall or winter. During those times, they can be handled more freely, but should still be prevented from drying out. When transporting from the nursery, holding, or harvesting area to the project site, this should be in a covered vehicle. If the weather is very hot, cooling from ice or refrigeration may be necessary. Exposure to high winds should be avoided. Plants can be placed in a water-filled ditch or covered with soil in a shaded area for storage of several days while awaiting planting. It is best not to store plants longer than necessary, and delivery should be scheduled to match planting dates.

If herbaceous plants are to be grown, they will need to be grown from seed or from collected rhizomes, tubers, or rooted stems or rootstock from the wild. Most wetland plant seed needs to be stratified and will not germinate underwater even after stratification. An experienced wetlands nursery person should be consulted before attempting to grow wetland plants from seed. Often, a cold treatment underwater is necessary for stratification (Pierce 1994). There are various other stratification methods of wetland plants, such as hot and cold temperature treatments and treatments with various fertilizers. Rhizomes, tubers, and rooted stems and rootstock of wetland herbaceous plants can be grown out in wet troughs or ditches and ponds containing fertilized sand and peat moss. Only enough water is

necessary to keep the rhizomes, tubers, etc., from drying out. Plants can be grown out in the greenhouse over colder months, but will require hardening before transfer to the project site.

Hoag (1994b) stated that hardening off can be accomplished by removing the plants from the greenhouse and placing them in a cool, partially shaded area for 1-2 weeks. This is generally a lathe or slat house. Some are constructed with snow fencing, which has wooden slats woven together with wire. According to Hoag (1994b), this type of structure allows a small amount of direct sunlight and solar radiation through the slats to the plants, but not enough to burn them. A partially shaded spot near the planting site will also work. It is important to keep the plants well watered and misted during the hardening off period.

Timing of Planting

Woody plants

Woody cuttings and transplants should always be planted in the dormant season for best chance of survival and growth. If they cannot be planted in the dormant season, they should be held in cold storage, around 28 °F, until they can be planted. Refrigerated trucks or vans are often used for this. Sometimes, storage lockers can be found and rented to keep materials dormant. Woody plants can be considered dormant when their buds are set in the fall, usually after the first hard freeze, until late winter to early spring when buds are noticed to swell.

Whether to plant in the fall or late winter-early spring will depend upon the hydrology of the stream system in which one is working and the climatic conditions. If water levels are expected to be down in the fall and winter and if plants can obtain growth in the early spring prior to flood events, then planting at that time may make sense. Conversely, if water levels may fluctuate dramatically during the dormant season with accompanying high velocities, then it may make sense to plant in the late spring after the threat of flood events. In any case, it is best to choose a planting period where water levels are apt to be at normal flow levels or near normal flow levels, if possible.

According to Leiser (1994), fall plantings may be preferred in areas with late growing seasons, winter rains, and summer drought. This allows a longer period of establishment before late spring when flooding or drought occurs. However, bare-root plants may not be available until late fall or even mid-winter. Late fall plantings may not be desirable where late fall droughts occur, or where frost heaving is severe before new root growth occurs. Spring planting dates are usually required for bare-root stock, where sites are subject to late fall and winter frost heaving problems, or where flooding occurs in late fall to early spring. Spring planting should be scheduled as early as site conditions permit. Summer plantings should be avoided.

Herbaceous plants

Herbaceous plants, such as emergent aquatic plants, can be planted during both dormant and nondormant times of the year. However, if they are planted in the nondormant season, they should be planted as early in the spring as possible to capitalize on maximum growth during the growing season. Plantings during hot, summer months should be avoided because of the risk of drying plant stock and associated planting shock and possible mortality. If planted during the dormant season, attention should still be given to the risk of flooding and current velocities that may wash the plants away before they have a chance to establish their roots in the substrate.

4 Monitoring and Aftercare

Philosophy of Monitoring and Aftercare

Most agencies and private entities cannot afford extensive monitoring in an operational setting in contrast to very definitive monitoring in a research and development setting. This discussion focuses on the operational setting. Bioengineering projects continue to grow stronger and stronger, once bed degradation is controlled, toe undercutting and scouring at upper and lower ends of reach have been arrested, and plants become established. Deeply penetrating plant roots hold the soil together, and upper stems deflect current and wave energy and slow local flow velocities. Then, sedimentation takes place and other pioneer plants start to invade and further contribute to stability. The key, however, is to ensure that this early-on establishment of plants takes place, and this requires early monitoring and possible remediation. Thus, early maintenance may be called for if this establishment is jeopardized. In contrast, traditional projects such as riprapped revetment may not require maintenance early in the project life, but may need major maintenance at a much higher cost a few years later. So, bioengineering may require early-on monitoring and remediation with the trade-off being no maintenance or little maintenance in later years. Figure 43 (from Coppin and Richards 1990) illustrates this point.

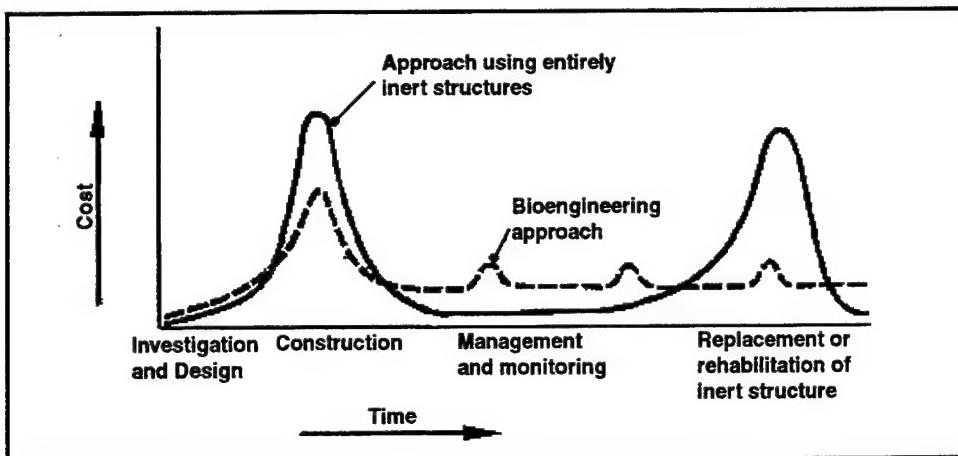


Figure 43. Illustrations of different expenditure profiles and maintenance (implied) of inert structures and bioengineering treatments (from Coppin and Richards 1990)

Bioengineering projects need to be observed early after project construction for signs of plant survival and development, as well as for streambank integrity. At least qualitative monitoring should be done to ensure that detrimental phenomena do not jeopardize the project. For instance, Court Creek, Illinois, one of the project case studies discussed in Report 2 had an infestation of spider mites. Within a month or so after planting, spider mites had damaged almost all of the leaves on the willow that were being used for stabilization. Without remedial spraying, project failure could have resulted. In another case study, North River, Massachusetts (Report 2), a drought occurred the first year after planting and killed much of the planted emergent aquatic vegetation. Remedial planting had to be done the following year to compensate for drought mortality. Also, along with vegetative development, streambank integrity needs to be observed to ensure that unraveling of the bank is not occurring from such actions as undercutting of the toe or flanking at the upper or lower ends of the treated section. If this is occurring, then corrective measures need to be taken immediately, such as placing more rock or some other hard structure in those places. Projects should be monitored at least a couple of years after development at a minimum. Preferably, they should be monitored through 1-2 flood events where currents are directed on the treated bank. One can then assess whether the site remains stable or unravels. In the latter case, remediation can occur. Site monitoring in bioengineering projects should be written into the contract specifications so that early remediation does not become a part of operational and maintenance costs, which often have to be budgeted separately within many agencies.

Direct Documentation of Erosion Protection

Aerial photographic monitoring

Each bioengineering reach and associated treatment, e.g., rock toe with brush matting, vegetative geogrid, should be monitored for erosion directly by use of aerial photogrammetric techniques. This will allow evaluation of changes occurring at the land-water interface providing the procedures discussed below are used.

Aerial photo coverage should be flown at least twice a year for the first 2-3 years or immediately after a flood event. Suggested times are in the spring and in the fall. Low-water periods are preferable. Photo flights should be highly controlled; that is, the scale of repeated flights must be the same. A suggested scale is 1:1,000. Also, three ground control points of known location and dimensions should be used per frame to provide accurate photogrammetric measurements, and these should be orthogonally corrected when processed to negate distortion. Recommended film type in priority order is (a) color infrared and (b) color. To allow comparisons of repeated photo coverage, flights must be made during low-water periods and when river water levels correspond to each other; that is, at or below previous photographic periods. Overlays can be made on the photos that will delineate the water-interface boundary. Subsequent overlays can be compared showing any changes in the water-interface boundary (see

Figure 44). Photographic measurements can then be made on the overlays to determine amount of surface area lost to erosion.

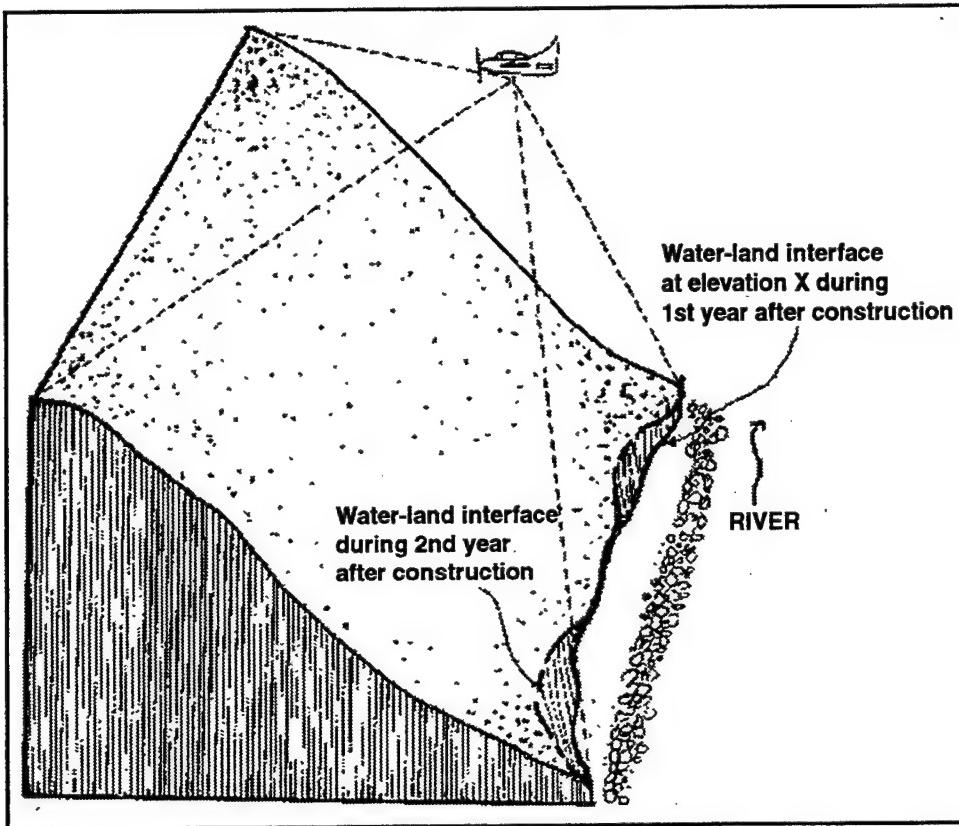


Figure 44. Aerial monitoring of bioengineering treatment (from Logan et al. 1979)

Ground photographic coverage

Monitoring, at a minimum, should be an array of photographs taken from the same photo point in the same directions so that later comparisons of streambank development or degradation can occur very readily. Preferably, this will be used to supplement the aerial photo coverage and measurements mentioned above. Photos should be taken at established photo points with photos taken periodically for a given azimuth. These should be taken at the same time the aerial photos are taken, again at low-water periods, if possible; however, others can be taken at intermittent times if deemed necessary.

Ocular description

As a further effort to document erosion, a description of any erosive processes must be made at the same time the ground photos are made. Processes that must be documented and particularly noted include such things as slumping from geotechnical failures, rilling, gullying, toe undercutting or launching, flanking at upper or lower ends of treatment, and

scouring at other areas within the reach from either current or wave action. Descriptive estimates of degree of severity for each of the above processes per treatment and reach with backup photos should be made.

Indirect Documentation of Erosion Protection

Erosion protection is assumed to be offered by the vegetation if the plants are surviving and developing; that is, covering the site. The development of the vegetation needs to be monitored and possibly correlated, at least from a visual standpoint to the degree of erosion or lack of erosion taking place on the treated streambank. One would assume, for example, that vegetative plantings are doing a good job if the vegetation is growing well in all elevation zones in the project area and if the stream is not undercutting the treatments, flanking them, or scouring them to the point of failure.

Aftercare

As mentioned above, early monitoring may mean some early remediation and maintenance just to ensure long-term viability. What does this early remediation and maintenance mean? Does this constitute periodic irrigation or repeated fertilizer application? It does not as a regular rule. However, plants should be well watered immediately after planting. Bioengineering projects are normally installed at a time of the year, such as early spring, where precipitation is sufficient to allow the planted vegetation to sprout roots and stems and obtain a foothold in its environment. Plants may also be installed in the late fall during dormancy. Repeated irrigation is not needed then. Hopefully, fertilizer and other soil treatments were applied before or during planting, if needed, and they should not be required again, unless unusual circumstances prevail.

Possible aftercare requirements may mean bolstering a particular treatment with additional plants or even inert materials after an immediate flood event. Flooding may have caused some plants to wash out before they had a chance to secure themselves with their roots. Hopefully, engineered materials, such as wire, stakes, geotextile coverings, rock toes, etc., would have helped hold the plants and soil until the plants become established, but sometimes any one of these materials, either plants or inert materials, may need bolstering.

Other aftercare measures, as mentioned above, may mean treating plants with an insecticide or fungicide if insects or disease is widely prevalent. Usually, this will be the exception rather than the rule. One can overcome widespread insect or disease damage by emphasizing a wide diversity of plants in the plant mix so that if one species is attacked, the whole vegetative treatment will not be jeopardized. Beaver and herbivores, such as geese, may be a problem in some cases by feeding on woody and emergent aquatic plants, respectively. Beaver will often chew off the upper part of

willow and poplar cuttings, but these can resprout and still perform satisfactorily if the complete cutting or stem is not chewed off or dislodged. In some cases, where beaver are known to be in the area, then a trapping program may be advised. Waterfowl, especially geese and swans, like to grub out emergent aquatic plants as well as feed on the upper parts. Temporary fence corridors made out of wooden slats with tiered twine attached to the slats have been shown to prevent geese from feeding on emergent aquatic plants. They do not like to feel trapped inside narrow confines where they cannot escape quickly.

5 Costs of Bioengineering

Bioengineering treatments are normally much less expensive than traditional methods of streambank erosion control, e.g., riprapped revetment, bulkheads, but not always depending on the environmental setting and the project objectives. Costs can vary tremendously by availability of materials, hauling distances, prevailing labor rates for the geographic area, and a host of other factors. Table 3 illustrates cost comparisons of actual costs for a couple of bioengineering installations compared with estimated costs of riprapped revetment for the same locality under similar conditions. One will note that the first method, the dormant post method, installed in northwestern Illinois, was about one-fourth the estimated cost of riprapped revetment. The vegetative geogrid installed in California was about four times the estimated cost of riprapped revetment. In the first case, riprap

Table 3
Comparisons of Actual Costs of Bioengineering Treatments With Estimated Costs of Traditional Erosion Control (riprapped revetment) Under Similar Conditions in Same Area

Location and Conditions	Type of Treatment	Costs, \$/lin ft
Court Creek, IL		
10-ft bank height; 3.1 fps local velocity; 1V:1H graded side slope	Dormant post and rock toe	\$15.19 (actual)
10-ft bank height; 1V:2H side slope; 1.5 ft total rock thickness, (0.5 ft bedding material); 300# stone size; 1.5 ton/ft; \$40.00/ton delivered and placed	Riprapped revetment	\$60.00 (est.)
Upper Truckee River, CA		
6-ft bank height; 4 fps local velocity; stacked soil lifts	Vegetative geogrid	\$104.00 (actual)
8-ft bank height (2-ft buried); 1V:2H side slope; 18 sq ft rock/ft; \$20.00/ton delivered and placed	Riprapped revetment	\$27.00 (est.)

was in short supply and cost much more, which, in part, contributed to a higher cost than in the California example. Also, the dormant post method required cheaper materials and less labor than the vegetative geogrid in California. Riprap in the California example was fairly cheap, and the slope distance to cover the bank was not great, contributing to a cheaper installation than the vegetative geogrid. Also, the vegetative geogrid was fairly labor intensive. Labor accounted for 66 percent of the overall costs. However, what is not shown in the California example is that the site is next to a valuable golf course, and the sponsor is also trying to provide shaded riverine aquatic (SRA) habitat for native brown trout. The vegetative geogrid can be installed on nearly a vertical slope without much sacrifice to the adjacent land, and it will provide the SRA habitat shade by providing willow that overhang the banks. The riprapped revetment option does not provide overhanging vegetation for good SRA habitat and does require more land to accommodate shaving the bank to an acceptable construction standard for riprap. It would have required eliminating some of the valuable golf course land. Thus, one must consider the project objectives and potential benefits and impacts when considering comparison of bioengineering methods with other traditional techniques.

When comparing bioengineering methods with traditional engineering applications, Coppin and Richards (1990) stated that each must be considered on its merits, comparing life-cycle costs, i.e., the net present value of investigation, design and construction, plus future management and replacement. As mentioned earlier, bioengineering will require a higher investment early in the project life to ensure that the living system is established. Then, maintenance drops off and the vegetation in the bioengineering treatment continues to grow, spread, and strengthen the streambank through its various attributes mentioned early in this report. Some maintenance costs may be associated with the bioengineering treatment later in the project life, but these costs will be rather small. In contrast, the traditional treatment using inert structures, such as riprapped revetment, will have a high construction cost, a finite serviceable life with an element of maintenance, and then a substantial replacement or refurbishment cost (Coppin and Richards 1990). Figure 43 effectively illustrates this cost comparison (Coppin and Richards 1990).

Costs are also difficult to compare when strictly looking at currency per unit of measure. The most common denominator for arriving at costs seems to be labor in terms of person hours it takes to build and install the particular treatment. Then, material costs and equipment rental, etc., have to be added onto this. The authors could not document time for all of the bioengineering methods mentioned in the text, but some man-power estimates are given in the following paragraphs. Also, man-power costs are given for general applications of seeding and vegetative plantings to supplement the bioengineering treatments.

Man-Hour Costs of Bioengineering Treatments

Brush mattress or matting

The cost of the brush mattress is moderate according to Schiechtl (1980), requiring 2 to 5 man-hours per square meter. In a training session that WES conducted, a crew of 20 students using hand tools installed about 18 sq m of brush mattress at a rate of about 1 man-hour per square meter. This rate included harvesting the brush, cutting branches into appropriate lengths, and constructing the mattress. This rate of production compares favorably with an average rate of 0.92 sq m of brush mattress per man-hour by a leading bioengineering firm in the United States.

Brush layering

There are few references on the cost of brush layering. Schiechtl (1980) reported the cost to be low, presumably in comparison to techniques using riprap or other similar materials. In the training session mentioned earlier, a crew of 20 students using hand tools installed about 20 m of brush layering along one contour-slope in about 30 min. This equates to 2 m per man-hour. Often, costs can be reduced if machinery such as bulldozers or graders can gain access to the shoreline site and reduce the hand labor required in digging the trenches. Then, this would only require workers to fill the trenches with brush, which can also be covered with machinery.

Wattling bundles (fascines) and cuttings

Leiser (1983) reported man-hour costs for installing wattling and willow cuttings at Lake Tahoe, California (Table 4). These man-hour costs can be extrapolated to streambanks as well and run about 6 lin ft of wattling per man-hour and 46 small willow cuttings per man-hour. Robin Sotir quoted an average installation rate of 5 lin ft of fascine production per man-hour. Obviously, if one were to place a coir fabric between contours of wattling bundles, production rates would decrease substantially. According to Ms. Sotir,¹ who has done this extensively, it would probably half the amount of linear feet per man-hour.¹

¹ Personal Communication, 2 August 1996, Ms. Robin Sotir, President, Robin Sotir and Associates, Marietta, GA.

Table 4
Man-Hour Costs of Installing Wattling and Willow Cuttings at Lake Tahoe in 1973 (Leiser 1983)

Labor	Man-Hours
Prepare and Install Wattling (1,140 lin ft)	
• Scaling or cutting back the bank or slope	2
• Cutting willow whips	27
• Prepare (stack, tie, load)	28
• Layout	9
• Install	75
• Downtime (rain)	10
• Travel (from Sacramento, Marysville)	42
	193
Unit Man-Hour Cost: 1,140/193 = 5.9 lin ft per man-hour	
Prepare and Plant Willow Cuttings (8,000 cuttings)	
• Scaling	2
• Cutting	9
• Prepare	34
• Plant	76
• Downtime (rain)	10
• Travel (from Sacramento, Marysville)	42
	173
Unit Man-Hour Cost: 8,000/173 = 46.2 cuttings per man-hour	

Dormant willow post method

Roseboom reported that for bioengineering work on a 600-ft reach at Court Creek, Illinois, it took five men two 8-hr days to install 675 willow (12-ft-tall) posts on 4-ft centers.¹ This also included installation of a rock toe (20 tons of 10-in. riprap) with a coir geotextile roll along 300 ft. Also, 60 cedar trees were laid and cabled along the toe of the slope to trap sediment. This included an excavator operator along with the four other men previously mentioned. This equates to about 17 posts per man-hour that includes harvesting and installing the willow posts plus the other operations mentioned above, e.g., shaping site, cedar tree installation.

¹ Unpublished Report, 1995, D. Roseboom, T. Hill, J. Rodstater, L. Duong, and J. Beardsley, "Installation and monitoring of willow post bank stabilization enhancements, Peoria, Illinois," Contract No. DACW39-95M-4228, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Vegetative geogrid

Man-hour costs for 123 ft of a 6-ft-high vegetative geogrid installed on the Upper Truckee River that was previously mentioned included the following:

Three days time of:

- 1 Foreman/equipment operator
- 1 Equipment operator
- 2 Laborers
- 1 Supervisor/project manager

Thus, 120 man-hours were expended on the above project assuming an 8-hr day. This equates to about 1 man-hour per linear foot of treated bank. About 66 percent of the costs of this treatment can be attributed to labor.

Man-Hour Costs of Standard Vegetation Establishment Techniques to Supplement Bioengineering Treatments

Standard seeding

The cost for broadcast seeding per square meter can vary considerably according to some literature sources. Reported costs in man-hours per square meter vary from 0.004 (Kay 1978) to 0.07 (Schiechtl 1980) depending on the degree of slope and the type of seeds used.

Hydroseeding

Depending on the material used and the distance to adequate water, 4,000 to 20,000 sq m can be hydroseeded by one hydroseeder machine per day (Schiechtl 1980). A hydroseeder normally uses a two-man crew.

Hydromulching

Mulching is often applied over seeds by a hydromulcher similar to a hydroseeding machine. For hydromulching or mechanical mulching without seeds, about 0.12 to 0.50 man-hours per square meter is estimated (Schiechtl 1980). Mulching after seeding increases the cost per square meter considerably. Hydromulching with a slurry of wood fiber, seed, and fertilizer can result in a cost of only 0.008 man-hour per square meter, according to calculations derived from Kay (1978), who reviewed contractor costs in California. The above man-hour calculations assume the following: use of a four-man mulching machine, seed and fertilizer applied at a rate of 0.75 ton per acre, and an application rate of 2 tons per hour.

Sprigs, rootstocks or plugs, rhizomes, and tubers

Costs for digging grasses and other herbaceous plants in their native habitat and transplanting propagules of these will vary depending on the harvesting system used, the placement of the plants, and the site. For digging, storing and handling, and planting 1,000 plants of sprigged wetland grasses and sedges, Knutson and Inskeep (1982) reported a rate of about 10 man-hours. Sprigs of this type were placed on 0.5-m centers, which would cover 250 sq m. For the same kinds of plants, Allen, Webb, and Shirley (1984) reported a rate equivalent to 400 plants per 10 man-hours for digging, handling, and planting single sprigs. According to Knutson and Inskeep (1982), using plugs of any species (grass or forb) is at least three times more time-consuming than using sprigs (30 man-hours per 1,000 plugs).

Bare-root tree or shrub seedlings

Depending on type of plant and local conditions, the reported costs of planting vary considerably. On good sites with deep soils and gentle slopes, the authors have experienced planting up to between 100 and 125 plants per man-hour. Logan et al. (1979), however, estimated that only 200 to 400 plants per day per person could be achieved on sites like the banks of the upper Missouri River.

Ball and burlap trees or shrubs

Planting costs for this type of transplant will range from 10 to 25 plants per man-hour (Schiechtl 1980).

Containerized plantings

The cost of plantings varies depending on plant species, pot type, and site conditions. By using pots other than paper, 20 to 40 plants per man-hour can be planted. With paper pots, up to 100 plants per man-hour can be planted (Schiechtl 1980). Logan et al. (1979) stated that the cost for hand-planting containerized stock ranges from one-half the cost for bare-root seedlings to a cost equal to or exceeding that of the container seedling.

6 Summary and Recommendations

Bioengineering can be a useful tool in controlling bank erosion, but should not be considered a panacea. It needs to be performed in a prudent manner and in consonance with good planform and channel bed stability design. It must be done with the landscape and watershed in mind, particularly with respect to erosion that has occurred as a result of both broad basinwide activities and local, site-specific causes. Nevertheless, bioengineering must be done at the reach level. This must be done in a systematic way with thought given to its effects both upstream and downstream, and it may have to be done incrementally to overcome seasonal time constraints. For instance, woody plants must be planted in the dormant season. There are numerous questions that must be answered prior to bioengineering implementation. Answering these questions and designing a project must be an integrated process that starts with the planning phase and continues through the construction phase. There are obviously feedback loops from the design and construction phases back to the planning phase. Additional information may have to be retrieved that calls for more planning actions.

Bioengineering must be accomplished with enough hardness to prevent both undercutting of the streambank toe and erosion of the upper and lower ends (flanking) of the treated reach. This can be done with one or both of (a) hard toe and flanking protection, e.g., rock riprap, refusals, and (b) deflection of water away from the target reach to be protected through deflection structures, e.g., groins, hard points, vanes, and dikes. With both of these methods, only appropriate plant species should be used in a manner consistent with their natural habitats. This is often done by using streambank zones that correspond with microhabitats of native plant species in local stream environments. Where possible, both herbaceous and woody species are used with grass or grass-like plants, e.g., sedges, rushes, reed grasses, in the lower-most zone, then shrubby, woody vegetation in the middle zone, and for the most part, larger shrubs and trees in the upper-most zone. These zones are respectively called the "splash, bank, and terrace zones."

Careful planning must be done to acquire the kinds of plants in the amounts needed. This may take up to 1 year before installation of the various treatments because plants either have to be grown in sufficient

quantities in nurseries, or they have to be located in the wild and either collected or grown from wild plant stock.

Bioengineering treatments have been noted, depending on the type of treatment, to resist up to 12 fps local flow velocities. It is recognized, however, that local flow velocities during peak discharges are difficult to obtain during those events because of safety considerations. Log revetments with geotextile rolls in Colorado sustained velocities up to 10 fps, but undermining the lower logs occurred in the lower part of the treated reach. A general rule of thumb is that for velocities exceeding 8 fps, some combination of inert material be used with plants that are well secured and have adequate toe and flank protection. The inert material may be deflection structures made from root wads or rock hard points or dikes, etc., or the inert material may be wire and stakes that hold down plant material long enough for that material to take hold. Even then, those materials, both inert and living plants, must have enough toe and flank protection to allow sustainment through flood events. This sustainment is especially critical during the early phases of the project.

Early monitoring and aftercare of a bioengineering project is essential. Each project should have incorporated into it from the beginning enough time and funds to provide some remedial work within the first year or so after treatment installation. It would be better to provide this contingency for up to and immediately after the first one or two flood events. Once weak spots in treatments are repaired, the bioengineered system continues to gain strength over time.

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